BIOENERGY MODELLING FOR SOUTHERN AFRICA - BENCHMARKING NAMIBIA AND SOUTH AFRICA

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SUMMARY

Namibia and South Africa as part of Southern Africa are focussing on new technologies which on the one hand have the capacity to address energy shortages, particularly to increase power generation capacity; and on the other hand fulfil socio-economic development goals with minimal negative environmental impact. Bio-oil as a product from fast pyrolysis lends itself towards bioenergy production; to serve as a liquid fuel both for heat production and/or to fuel stationary engines or power generating equipment. Fast pyrolysis is a relatively new technology globally; and not yet introduced to Southern Africa. This research therefore describes bioenergy production via fast pyrolysis systems. The potential of the bioenergy so produced is investigated in terms of its potential to fill energy gaps, particularly power, as well as to fulfil socio-economic and environmental conservation targets in Namibia and South Africa.

Namibia and South Africa possess vast wood-based biomass resources which can be converted to bioenergy via fast pyrolysis. This research models the wood-based biomass resources available for bioenergy production in Namibia and South Africa respectively; describes their physical and chemical properties and provides information on where they are located within, and how they can be harvested in a sustainable manner in Namibia and South Africa.

The analysis to introduce fast pyrolysis into the Namibia and South Africa is based on an in-depth review of past experiences with pyrolysis technologies and the types of products successfully sold from various pyrolysis operations. The results of biomass modelling and description are used to model a bioenergy production system via fast pyrolysis.

In Namibia fast pyrolysis operations are focusing on power generation in the Otjiwarongo and Okakarara farmland area, with a capacity of up to 20MW over a 20-year period. The power so generated is based on wood from bush encroachment only. In South Africa, the wood-based resource, i.e. alien plant species and bush encroachment, could provide communities in three provinces with at least 1MW but not more than 5MW power respectively over a period of at least 20 years. However, the introduction of new technologies and their products, such as fast pyrolysis and bio-oil for bioenergy production to Namibian and South African markets would be cumbersome. Technical and non-technical as well regulatory barriers have been identified; these need to be overcome before fast pyrolysis is accepted in the market.

Key words: fast pyrolysis, slow pyrolysis, bio-oil, bush encroachment, alien plant species

TO MY FAMILY

I LOVE AND THANK YOU

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LIST OF ABBREVIATIONS

BTL	Biomass to Liquids
FT	Fischer-Tropsch or methanol synthesis
HHV	higher heating value
LHV	lower heating value
MTG	methanol to gasoline
MOGD	methanol to olefins, gasoline and diesel
VOH	vegetable oil hydro-processing, yeast biotechnology and conventional biodiesel by trans-esterification of fatty acids.

LIST OF UNITS OF MEASURE

HHV higher heating value, or standard heat of combustion, is the gross heating value measured on a fuel (in this case wood based biomass or bio-oil depending which technology 'uses' the fuel), weight basis; measured in MJ/kg. The HHV takes into account the latent heat of vaporisation of water in the combustion process.

LHV lower heating value, or net calorific value, is the net heating value measured on a fuel (in this case wood based biomass or bio-oil depending which technology 'uses' the feedstock), weight basis; measured in MJ/kg. Technically, the lower heating value of a fuel is defined as the amount of heat released in the combustion of the fuel to give products at 150˚C. The LHV assumes that the latent heat of vaporisation of water in the reaction products is not recovered.

Mt million tonnes = 10^9 kg

Mtoe Mega tonnes oil equivalent is 10^9 kg; unit of energy quantity, worldwide used as unit for energy consumption or production of a country

J joule, the metric unit of energy

PJ Peta Joule = 10^{15} Joule

MW Megawatt; unit of power generation capacity used for fossil resources based plants and, in this work, wood based biomass based power plants

MWh Mega Watt hour = 10^3 kWh

1 INTRODUCTION

This research aims to explain how fast pyrolysis technology could be introduced and the benefits of using fast pyrolysis to produce bioenergy (section 1.4 and chapters 7, 8, 9) in Namibia and South Africa. Opportunities for downstream processing of wood-based biomass in Namibia and South Africa exist; and fast pyrolysis offers the suitable technology to pursue this potential, also based on the industrialisation policies promoted. The Southern African region has vast wood-based biomass resources available (Chapter 6) which can be converted by fast pyrolysis to derive bioenergy to generate electricity in the Southern African region. Pyrolysis of biomass at moderate temperatures (400-600ºC) produces three products; pyrolysis liquids, char and gas. Depending on the retention time and size of the biomass to be converted, the yields of the respective products can be influenced, and either more char or more pyrolysis liquid is produced. When char is the primary product, the process is referred to as slow pyrolysis. When the primary product is produced in high yield of usually above 60wt.% of the dry biomass feed and is a homogenous single phase liquid (bio-oil), this process is referred to as fast pyrolysis. Bio-oil derived from the fast pyrolysis process can be combusted as an alternative to fuel oil, to be used e.g. for electricity or heat generation. Alternatives are to use fast pyrolysis to make energy carriers for export, and/or biofuels, and/or chemicals. This research focusses on bioenergy possibilities via fast pyrolysis to make energy carriers for export and biofuels to be combusted mainly for electricity generation within Namibia and South Africa. In this context, ‘bioenergy’ is used as the generic term.

Combustion or gasification of biomass, which are more proven technologies, is arguably better for power generation. However, conversion of wood-based biomass resources in Namibia and South Africa by fast pyrolysis is chosen for this research because of familiarity of pyrolysis processes in general in Southern Africa; versatility in choice of products; ease of transportation of the liquid (bio-oil) and solid products (char) for export; and an existing infrastructure of maintenance and repair. Pyrolysis type technologies are familiar in the Southern African region due to the experience in charcoal manufacturing.

This research had two main objectives. Firstly, to determine the parameters which could result in a sustainable fast pyrolysis industry in Namibia and South Africa to derive bioenergy. Secondly, to develop a guide or roadmap which could result in a selective increase in the use of the wood based biomass potential to yield energy (hereafter referred to as bioenergy or biofuels) in Namibia and South Africa. Extraction of useful chemicals from wood-based biomass and markets for them is discussed, but not to the same level of detail as for bioenergy potential.

1.1 BACKGROUND

This research was concentrated on the bioenergy potential in Southern Africa; Namibia and South Africa were selected to establish such bioenergy potential. These countries have a large wood biomass resource base and a strong technological and socio-economic development base which can be used to advance the bioenergy industry via fast pyrolysis in the Southern African region. It is acknowledged that many renewable resources exist in Southern Africa, and that the bioenergy potential of a country can also be tapped via hydro-liquefaction, fermentation technologies, aqueous phase reforming, trans-esterification of vegetable oils and other processes. However, technology advancement is limited and technological and socio-economic opportunities from using such technologies are not utilised [35]. In contrast, pyrolysis processes have been practiced in Southern Africa over at least four decades (Table 4-6). Namibia and South Africa (and where South Africa imports charcoal from neighbouring countries) extensively use slow pyrolysis, i.e. kiln technology to primarily produce charcoal for the local and export markets. The technological concept of fast pyrolysis for national bioenergy production is acknowledged by industry players in principle but is not used [1, 102, 116, 158].

The biomass resources in Namibia and South Africa which are considered in this research are available in abundance due to bush encroachment and invasion of alien wood species. Utilising wood from bush encroachment enables higher productivity in the agricultural sector in Namibia, and of particular interest is the livestock production sector. In the South African case, invasion by alien plant species should be eradicated to reinstate biodiversity (Chapter 3 and section 4.1.5). In both Namibia and South Africa, a vast amount of biomass would become available for bioenergy production without creating unwanted deforestation.

Internationally, the growth of the bioenergy industry has been driven by a number of factors which includes: support for cleaner and environmentally friendly energy sources in a bid to limit climate change; promotion of the agricultural sector through utilisation of surplus agricultural land to produce products in excess of food needs; promotion of sustainable development; and the need to improve energy security.

In developing countries like Namibia and in emerging economies like South Africa, there is a need for a new approach towards fast-tracked economic development. The bioenergy sector, and in particular production of energy via fast pyrolysis, offers a number of opportunities for economic development, especially in Namibia where the bulk of electricity energy needs are imported [2, 3]. Equally, Namibia has no fossil fuel exploration or refinery; bulk storage capacity for liquid fuels, in to particular sustain manufacturing activities over the long term [4], is limited. Energy needs for manufacturing in Namibia are covered through the import of fossil based liquid fuels (e.g. crude oil or Diesel), mainly from South Africa. Nonetheless, no state incentives towards fast pyrolysis for bioenergy production systems exist to promote the opportunities that energy production from biomass offer for economic development. This research aims to highlight what needs to be considered to introduce fast pyrolysis to Namibia and South Africa for multiple reasons:

- Fast pyrolysis is not only a new technology to Namibia and South Africa, it is also largely unknown; however, fast pyrolysis technologies, compared to the better known slow pyrolysis technologies, can more efficiently and effectively convert abundantly available wood-based biomass to energy [5].
- Where commercialised fast pyrolysis technologies may be available, their high costs do not make them financially viable as they are more expensive than existing systems based on fossil energy sources (Chapter 8, 9 and 9.9). Provision of state incentives would enable decentralised pyrolysis technology deployment close to the wood-based biomass resources and in proximity of bioenergy markets, like power generation plants.
- Biomass from invader and/or alien invasive wood species is available in abundance; however, harvesting and logistical costs are high and therefore reduce the viability of the production of energy via fast pyrolysis.

Namibia [6] and South Africa [30] have recently promulgated their industrial development policies. From these policies, various types of renewable energy sources are acknowledged to enable development of new industries based on the use of renewable energy. In particular, energy generation from biomass for production of electricity was cited as a major objective. However, the governments of Namibia and South Africa recognise that clear government policies, regulations and incentives are a pre-requisite for development of a successful bioenergy industry. The regulations need to incentivise new industrial developments, including research and promotion for the use of these 'new' forms of energy in line with the industrialisation policies [6, 30, 7]. In the Namibian case, bioenergy generation from bush encroachment and other forms of utilising the wood based biomass resources was cited [102] to be very important.

In contrast to fossil fuels, the use of biomass for energy provides significant environmental advantages, such as cleaner production methods and sustainability of the feedstock. Renewable biomass sources can be converted to fuels, for generating heat and electricity, and as transport fuels. Efforts have been made in Europe and North America to develop new processes for converting renewable biomass to energy [8, 62, 64, 65, 67, 29] via fast pyrolysis. A limited number of biomass slow pyrolysis conversion processes are practiced in Namibia and South Africa [7] (Chapter 4). These conversion processes are kept simple in technological terms, i.e. they involve a great deal of manual labour and mechanisation is limited. The manufacturing capability to utilise biomass resources to produce energy via slow pyrolysis processes on a large scale is too limited to contribute to national energy supply in a meaningful manner. Industrial policy directives should enable the upgrading of manufacturing capacity and technological adaptation.

Selected processes that convert wood-based biomass to liquid fuel begin with fast pyrolysis, followed by, for example, catalytic upgrading of bio-oil or bio-oil gasification in conjunction with Fischer-Tropsch synthesis. There are various opportunities to convert biomass to fuels or chemicals with environmental benefits via the fast pyrolysis conversion route.

The biomass resource potential of the wooded lands of Namibia and South Africa together is estimated in excess of one billion tonnes per year (Chapter 5). However, audited statistics on energy production from, and consumption of wood-based biomass are limited in both Namibia and South Africa [9, 10]. Limited or absence of energy statistics make it very difficult to evaluate the contribution and potential of bioenergy in Namibia and South Africa.

South Africa used bioethanol from sugar cane in petrol from the 1920s until the 1960s; this subsequently stopped due to low international crude oil prices [7, 41, 142, 226]. Since 2006 persistently high oil prices and climate change considerations have led to renewed interest in bioenergy production. The interest in South Africa centres on biodiesel (by trans-esterification) and maize or sugar production residues' conversion to ethanol, mainly as a conventional fuel substitute. In the Namibian case liquid fuel from biomass is not practiced, nor has national interest arisen. The potential that fast pyrolysis offer for either liquid fuels and/or electricity generation are not known. Only the pyrolytic breakdown or thermal degradation of wood-based biomass residues, specifically via slow pyrolysis for the production of charcoal are practiced. This is discussed in detail in Chapter 4.

1.2 OBJECTIVES

The primary objectives of this research are to:

- Collect, analyse and model biomass resource data in Namibia and South Africa;
- Analyse, evaluate and provide recommendations on the current and predicted Namibian and South African fast pyrolysis industry;
- Analyse and evaluate opportunities for the use of fast pyrolysis to convert the wood-based biomass into bioenergy in Namibia and South Africa.
- Assess the environmental and techno-economic sustainability of fast pyrolysis systems to produce bioenergy (e.g., power, heat, fuel) from wood-based biomass resources in Namibia and South Africa.

To fulfil the primary objectives, the scope of work in more detail relates to:

- model wood-based biomass resources, identify opportunities, predict growth in potential wood-based biomass production in Namibia and South Africa;
- assess how slow pyrolysis processes were used in wood-based biomass conversion to model the introduction of fast pyrolysis processes to Namibia and South Africa for future bioenergy opportunities and practices;
- produce a techno-economic model of opportunities for improved use in relation to uptake, efficiency and effectiveness of wood-based biomass resources for biofuels (char, liquid or gas), heat and power, in Namibia and South Africa, including future prediction, opportunities and constraints;
- assess the feasibility and viability of fast pyrolysis on technical and socio-economic grounds; including present and future scenarios;
- provide a present and future ‘map’ of knowledge in relation to resources and skills of pyrolysis and its derived products in Namibia and South Africa;
- produce a list of knowledge and technology transfer possibilities for fast pyrolysis technology adaptability in Namibia and South Africa and the necessity of support systems/mechanisms for the deployment of these; and
- produce a “roadmap” for technology deployment and a timescale to achieve market penetration for products derived from fast pyrolysis.

1.3 RATIONALE TO BENCHMARK CERTAIN GEOGRAPHIC REGIONS AND COUNTRIES

With 53 sovereign states in Africa, the continent is home to a population of about one billion people. In general, the greatest economic activity to date is limited to selected countries in North Africa (Tunisia, Egypt, Morocco); West Africa (Ghana, Nigeria); East Africa (Kenya, Uganda, Ruanda) and Southern Africa (South Africa, Namibia, Botswana, Angola, Mozambique, Mauritius, Seychelles, Zambia). Economic growth of each of the latter mentioned countries were on average in excess of 3% per annum for the past five years. The governments in Southern Africa are of the opinion, that by continued expansive budgetary allocation [4, 11] to specific sectors of the economy, private local and foreign direct investment into the economies would follow, and thus give impetus to faster economic growth. With the aim of industrialising a country, private sector players are key. Governments' role is to sustain a conducive macro-economic environment and regulatory framework. The private sector is the engine of growth [12] and would seek out local and foreign direct investment options if market opportunities and technological readiness exist, skilled and trained labour is available and if the investments can be made at low risk (Chapter 9, section 9.8).

Allowing that the latter aspects need improvement, sufficient opportunities specifically in Southern Africa exist. The rationale for choosing Southern Africa as a region to be investigated further in relation to bio-energy supply is that natural and financial resources are in abundance; basic skills and knowledge of labour is available; the market seems to be sufficiently diversified and large enough to offer opportunity for new and/or adapted technologies and the derived products [4, 6, 7, 11, 16, 25, 26]. The knowledge of bioenergy use in the rest of Africa seems to be much more limited [249].

1.3.1 <u>Southern Africa</u>

Southern Africa refers to the countries located in Africa, south of the equator (Figure 1-1). Political demarcation generally limits countries of Southern Africa to those belonging to the Southern African Development Community (SADC), a 15 Member State association pursuing similar economic development goals, in a time bound and agreed manner. The economic milestones to be achieved include a customs union by 2012 and a common monetary area by 2015. The SADC member states are: Republic of Angola, Republic of Botswana, Democratic Republic of Congo, Kingdom of Lesotho, Republic of Madagascar, Republic of Malawi, Republic of Mauritius, Republic of Mozambique, Republic of Namibia, Republic of Seychelles, Republic of South Africa, Kingdom of Swaziland, Republic of Tanzania, Republic of Zambia and Republic of Zimbabwe. More than 300 million people live in the SADC region.

Figure 1-1 Map of the Southern Africa region; Namibia lies to the south-west; South Africa to the most southern part of Africa [13]

The focus of this research within the Southern African region is on Namibia and South Africa. South Africa, as the most developed economy in Southern Africa, is presented as the point of reference. Although a much smaller economy, Namibian economic development status compares with that of South Africa in terms of law and order; wealth of natural resources; population dynamics and social challenges; and international commitments towards trade, environmental sustainability and human rights. South Africa's governance structures are more complex than those of Namibia. This research aimed to specifically highlight the differences and/or similarities in governance structures between Namibia and South Africa which relate to the utilisation of wood-based biomass resources to produce energy and to; propose how, for example, policies can be accommodated in the similar framework for modelling bioenergy production systems.

This study presents itself to provide fundamental research on bioenergy potential in Southern Africa. Namibia forms the basis for all models and scenarios to be developed: biomass and other resources; possibilities for introduction of new biomass conversion technology and the derived products; the ‘roadmap’ for fast pyrolysis technology deployment and socio-economic considerations in certain aspects. Market uptake for products derived is mainly based on South African scenarios. Following World War I, in 1915, Namibia (then known as South-West Africa) was administered by South Africa, as mandated by the League of Nations. Political independence of Namibia from South Africa was gained in 1990. Economically, Namibia remains very dependent on the South African economy.

1.3.2 Namibia

Namibia means the Republic of Namibia. Independent from the Republic of South Africa since 21 March 1990. Namibia’s size is 824 thousand km^2, with a population of 2.2 million [14]. Namibia is classified as a high-Middle Income Country [15], based on the average per capita income of approximately USD 4,000 per annum, however the standards of living in Namibia vary widely. The income distribution is extremely skewed and the majority of the people living in rural areas make use of subsistence farming to sustain their livelihoods, adding further ecological pressure on land suitable for livestock production. Due to the large extent of subsistence farming, the agricultural sector, including forest based activities, is the biggest employer. Although in terms of contribution to economic output, mining and services are the most important sectors. The economic development stage is largely classified as resource based, with large economic dependence (measured by trade balance) on South Africa. A large degree of industrialisation should be achieved by 2017 [6]. By 2030, Namibia aspires to be knowledge based and technology driven economy [16]. Namibia is a member of Southern African Development Community (SADC) and the Group of 77 (G77, is the group of developing and least developed countries outside the G20).

Namibia’s energy supply, both power and liquid fuel, to date is mainly imported from South Africa [17]. Policies exist that aim to improve the investment in local power generation [18] to substitute imported power. A further political aim is to sustain medium term liquid fuel supply through increased storage capacity of imported fuels [4], but it is uncertain how such increased storage capacity would improve energy supply and security. However, policies to produce liquid fuel locally as a long term solution are not available or are not promoted to date. Fundamental research and development is lacking [19, 20] which could act as a catalyst for appropriate policy development on the manufacture of liquid fuel. It seems that policies are developed in the absence of essential research.

Namibia’s natural resource base is vast, in terms of both land and wood-based biomass. Several trials have been run to sustainably utilise the biomass resources for various purposes; many of the trials failed (Chapter 5 and section 6.1). The reasons are not always clearly spelled out; speculations mostly hint to lack of detailed planning prior to investment and lack of commitment between parties involved after projects were commissioned.

1.3.3 South Africa

South Africa means the Republic of South Africa. South Africa measures 1.21 million km^2 in size and has a population of some 52 million [153, 154]. South Africa is classified as a high-Middle Income Country [15]. The governance structure of South Africa is at multiple levels; central government, provincial government and local/municipal level. The provinces and provincial governance cities are highlighted in Figure 1-2 [21].

Figure 1-2 South Africa political map, highlighting the location of provinces [21]

South Africa was admitted to the group of most influential emerging markets, BRIC-S (Brazil, Russia, India, China and now South Africa) in 2011. South Africa is member of the Group of 20 (G20), the world's 20 most influential nations, in terms of economic output, level of advanced economic development and political influence. The G20 consists of the Group of 8 (G8) plus 12 other member states. South Africa's economic output measured as GDP accounts for more than 70% of the combined SADC GDP. The economic development status is largely classified as industrialised. However, there are pockets in the country which are still underdeveloped where the population still largely lives off subsistence farming. Technological readiness and the level of innovation in South Africa is the highest in Southern Africa [22]. South Africa aspires to become a knowledge based economy by 2025 as outlined in the Accelerated and Shared Growth Initiative of South Africa - the AsgiSA [30].

South Africa has vast natural and mineral resources, including fossil fuel resources to cover its energy needs. To cover its additional energy needs for improved and complete industrialisation it imports [23, 24, 25] various resources which render energy, such as natural gas from Mozambique and wood and charcoal from Namibia. These imported energy sources are then, for example, converted to other energy types as in the case of natural gas to liquid fuels. Wood and charcoal are used for domestic energy purposes and as reduction material in mineral processes respectively. Furthermore, South Africa has adopted the "biofuels industrial strategy" [7] with the aim to invoke technological advancement and abide by international commitments, notably the UN Framework Convention on Climate Change (UNFCCC).

The economic partnership between Namibia and South Africa seems to come naturally. While South Africa imports key resources from Namibia, Namibia imports key processed goods, commodities and various types of services from South Africa. South Africa has a positive trade balance with Namibia, that is, South Africa exports more goods than it imports from Namibia. Opportunities exist to exchange knowledge and engage in technology transfer between the two countries. Broad scale political commitments have been made and are re-iterated [26, 27] which await implementation. This research concentrates on development possibilities that relate to the exchange of knowledge and technology transfer between Namibia and South Africa, specifically in the area of energy production from biomass resources via fast pyrolysis.

1.4 RATIONALE FOR BIOMASS FAST PYROLYSIS CONSIDERATIONS

Thermal degradation processes include liquefaction, gasification and pyrolysis. Pyrolysis converts organics to solid, liquid and gas by heating in the absence of oxygen. The amounts of solid, liquid and gaseous fractions formed is dependent on the process variables, mainly process temperature and speed, the type of biomass material used, and the distribution of products with each solid, liquid and gas phase produced.

This research concentrated on the bioenergy potential via fast pyrolysis in Namibia and South Africa other than by combustion, gasification or conventional biodiesel and bioethanol production. The latter processes are available as commercialised technologies used in South Africa especially, but fast pyrolysis is also of interest to Namibia. Pyrolysis, specifically slow pyrolysis, has been used in Namibia and South Africa to produce charcoal. The use of fast pyrolysis allows for the production of a liquid-state energy (bio-oil) which is of more consistent quality compared to solid biomass, and easier to handle. Thus the introduction of fast pyrolysis processes in these countries is of interest. Technological readiness and existing policies to increase liquid biofuels production in Namibia and South Africa for upgraded or other pyrolysis processes forms the basis for concentrating on fast pyrolysis. A further reason to concentrate on fast pyrolysis in this research is the readily available wood-based feedstock materials suitable for biofuels production via a fast pyrolysis process. Even though there is a fast pyrolysis technology manufacturer in South Africa [28], commercialised fast pyrolysis is not known to be used in South Africa nor in Namibia.

Since the 1970s, fundamental research on fast pyrolysis has shown that high yields of primary, non-equilibrium liquids and gases, including valuable chemicals, chemical intermediates, petrochemicals, and fuels could be obtained from carbonaceous feedstocks [29]. Fast pyrolysis can augment thermo-chemical conversion process output, i.e. the lower value solid char produced traditional slow pyrolysis compared to higher value fuel gas, fuel oil, or chemicals from fast pyrolysis. These can then be made available to render bioenergy sources.

Characteristics of wood fast pyrolysis products are dependent on whether a hardwood or softwood species is pyrolysed but the differences are largely insignificant for most applications. Both types of species are available in Namibia and South Africa. In addition, residues from processing deciduous fruit or agricultural production residues are available. The biomass resources, with the focus on wood-based biomass resources, showing potential for use in fast pyrolysis in Namibia and South Africa are discussed and described in Sections 3.1 and Chapter 5.

1.5 ORGANISATION OF THE THESIS

The thesis contains 11 chapters including this chapter.

Chapter 1 introduces the basis for the research; and the reasons why the research focuses on fast pyrolysis for Namibia and South Africa.

Chapter 2 explains the conceptual framework and the detailed approach to be used for this research. The conceptual framework is necessary to contextualise the primary objectives and scope of this research within the setting of the socio-economic status and the possibilities of wood-based biomass fast pyrolysis in Namibia and South Africa, as the benchmark for Southern

Africa.

Chapter 3 provides the definitions of terms and explanation of abbreviations or concepts used in this research.

Chapter 4 reviews the literature on biomass resources, techno-economic modelling of bioenergy systems by fast pyrolysis; costs for biomass energy, and markets for pyrolysis products. These aspects are reviewed in the Namibian and South African context of past performance, existing use and future options.

Chapter 5 provides the relevant data to be used in the models presented by the research. This chapter has become necessary as data is limited and not available publicly. However, a number of persons and institutions actually do keep data which they avail on a request basis. Much information therefore had to be retrieved and validated through personal discussions. By means of this research, information is made publicly available.

Chapter 6 models the wood-based biomass resources available for bioenergy production in Namibia and South Africa and presents estimates on how much wood-based biomass can be sustainably used as feedstock for fast pyrolysis in these countries.

Chapter 7 experimentally investigates some of the available wood-based biomass in Namibia and South Africa. Also included in this chapter is the calculation of mass and energy balances, as well as chemical analyses of the biomass as feedstock, char, non-condensable gases and bio-oil which provide the basis for assessment of significance and implementation of fast pyrolysis technology.

Chapter 8 describes techno-economic modelling for bioenergy production, based on results from experiments with some of the available wood-based biomass in Namibia and South Africa. The emphasis is on fast pyrolysis options modelling. This chapter further presents all assumptions and formulae underlying the bioenergy models for Namibia and South Africa respectively.

In **Chapter 9** the modelling results of wood-based biomass and technology options are reported and discussed. The results of the models are combined and assessed for their socio-economic feasibility in the Namibian and South African context.

Finally, the overall conclusions for the present work and the recommendations for future work are provided in **Chapter 10**. The recommendations are presented as a “roadmap” for possible fast pyrolysis technology deployment and timescale to achieve market penetration.

Chapter 11 provides an index of all references used for this research.

2 CONCEPTUAL FRAMEWORK OF STUDY

This chapter explains why alternative sources of energy are so important for Southern Africa, and in particular Namibia and South Africa. It provides a framework for the research carried out in terms of wood-based resources available and how they may be exploited to create a sustainable and viable alternative energy future for the region. The models to be created will be conceptualised in this chapter. The Namibian case forms the basis of the models. Where data or information is lacking in the Namibian case, South African experiences will be investigated and used where appropriate. The models to be derived should open up possibilities for future bioenergy alternatives based on fast pyrolysis technology. In line with the development of the respective models, these are evaluated and tested in later chapters.

The contextual framework is discussed against the backdrop of the socio-economic development goals in Namibia and South Africa respectively; international drivers to reduce greenhouse gas emissions globally; security of wood-based biomass supply; technological adaptability; and adaption of national policies or legislations to honour international commitments.

2.1 THE SOCIO-ECONOMIC SETTING

The South African Government and relevant stakeholders have embarked on an initiative to sustainably use natural resources like forests and woodlands, as a tool for general economic development [307, 30]. The objectives include: increased ownership of natural resources amongst poor and non-traditional land owners; as well as new effective market-based links created between the industry and the rural poor; improved industry standards and practices for contractors in the natural resources productive sector; and providing business support services to the rural poor, rural and micro, small, and medium size enterprises (MSME's) to facilitate participation in productive enterprises. Thereby achieving its development strategy presented in the AsgiSA – the Accelerated and Shared Growth Initiative of South Africa [30].

In Namibia, the socio-economic setting is mixed. On the one hand, economic growth is high at an average of 4% per annum [31]. In addition, foreign direct investment and foreign reserves are high, also by international standards [32]. On the other hand, unemployment is very high at 51.2% in 2010 [33] and decreased to some 40% in 2013 [34]; 80% of the unemployed have very limited skills or none at all, e.g. persons who have not completed school or never engaged in higher education and/or training development after leaving school. To address the skills shortages [35, 36, 37, 38] in Namibia requires additional research [39] which is beyond the scope of this study. But, for Namibia to be able to generate economic growth which is commensurate with employment created, skills development must be part of technology development and knowledge transfer. Since 1990, central Namibian government spending has focused on primary and secondary education at roughly 60% of total budget allocation to the education sector since 1990. Tertiary education and vocational training, including academic and applied research has attracted limited financial and human resources.

Namibia's agricultural sector, i.e. primary production, employing more than 40% of national workforce, suffers from declining output in terms of overall contribution to gross domestic product. Adverse climatic conditions, mainly due to long periods of drought in some parts of the country and recurrence of floods in other parts of the country, are one reason. Other reasons include bush encroachment which is said to negatively affect livestock production system (sections 3.4.1, 3.4.6, 5.1.2). The reasons for bush encroachment seem to be insufficiently researched; and the quantification of the spread is not well documented (section 5.1).

The Namibian government acknowledges that bush encroachment needs to be curbed to increase primary agricultural production [81, 90]. Especially extensive livestock production systems (section 3.4.7) are the mainstay of the agricultural sector in Namibia. The Namibian government acknowledges that bush encroachment is a resource for socio-economic development [16, 282, 86, 244, 247, 265, 89, 93]. However, beyond the latter acknowledgement no concrete policy interventions have followed to address bush encroachment to increase primary agricultural production output to date.

2.2 INTERNATIONAL DRIVERS AND NATIONAL POLICY

The AsgiSA and other initiatives are taking place in South Africa in tandem with the South African Government's commitments and international obligations to protect the environment. Conservation and sustainable use of natural resources is promoted to achieve multiple benefits and equitable distribution of wealth and resources. The South African government believes that it is important to adopt an integrated approach in managing natural resources [30, 125].

South Africa relies heavily on its vast coal resources to meet its energy demand [40]. In particular, South Africa has developed a large-scale, coal-based power generation system that provides low-cost electricity, supplied through the grid system that is being extended to rural areas, and to residential, commercial and institutional consumers. As a result, coal is and will likely remain an attractive source of energy for South Africa from an economic view point [40].

However, at the same time South Africa recognises that the emissions of greenhouse gases (GHG), notably carbon dioxide from the use of fossil fuels such as coal and petroleum products has led to increasing concerns worldwide [41, 42]. Furthermore, severe power shortages hamper economic development in the country as supply is not managed commensurate with growing demand. While the power grid has been extended heavily to cater for rural electrification since 1994, power generation capacity was not built [43, 44].

The combination of continuously increasing power demand and requirement by international commitments made to lower GHG, is a significant driver to find alternative solutions for clean, energy supply [42, 47, 45, 46]. Since 2008, demand for electricity outstripped supply and the national electricity provider ESKOM had to resort to load shedding [47]. To alleviate the electricity shortfall ESKOM has embarked on a power generation capacity expansion programme which includes about 10 GW of capacity from coal, through the construction of two new coal fired plants, and 1.2 GW from hydro power [47].

South African policy on industrial and economic planning seeks to ensure the integration of a diversity of resource materials into broader development issues, land use, natural resource management, and agricultural and energy planning. Interventions are sought to be built on best practices and to be aligned to regional and global techno-economic developments [40, 41].

At the Johannesburg World Summit on Sustainable Development in 2002, a commitment to promote renewable energy in all the participating nations was made, the Johannesburg Declaration [48]. In 2009, the South African Government re-affirmed its commitment to sustainable development by acceding to the Copenhagen Accord [115]. Correspondingly, it is the intention of the South African Government to make its due contribution to the global effort to mitigate greenhouse gas emissions and engage in sustainable development.

In the Namibian case, sustainable development and the protection of the environment is enshrined in its Constitution [49] and the Namibian government remains committed to sustainable development as per the Copenhagen Accord [115] and Kyoto Protocol [240]. However, commensurate detailed policies to promote the production of renewable energy and in particular bioenergy at national scale do not exist.

2.3 SECURITY OF SUPPLY, COSTING, MARKETS AND POLICY IN SOUTH AFRICA

Security of supply is understood in the context of both resource and feedstock supply to produce bioenergy, and the resultant supply of energy to the productive sectors and the population of Namibia and South Africa. Namibia and South Africa have an abundance of renewable energy sources that can be sustainable alternatives to fossil fuels (for various uses); these have remained largely untapped. The most common renewable energy sources currently utilised in South Africa and Namibia include solar, wind-energy and hydro for heat and power generation. There is limited industrial use of biomass for heat, power, fuel and / or chemicals [41, 50, 51]. No in-depth analysis of the wood-based biomass potential for the production of energy was found, providing an unique opportunity to investigate the feasibility of such resources as feedstock for energy production. This is described and discussed in Section 6.1 and 7.1.1 (Namibian wood biomass resources), Section 6.2 and 7.1.2 (South African wood biomass resources); modelled in Chapter 8 and discussed in Chapter 9.

The overall objective of the Government of South Africa's overarching policy on energy as set in its '*White Paper on the Energy Policy of the Republic of South Africa'* [41] and '*White Paper on Renewable Energy'* [40] pledges support for the development, demonstration and implementation of renewable energy sources for both small and large-scale applications. The latter policy guidelines reflect a renewable energy target of 10.000 GWH (0,8 Mtoe), of which 13 MW should be generated from biomass and another 13 MW should be generated from biogas by 2013. Subsequent to the policy directive to generate electricity from renewable resources [40, 41], the renewable energy feed-in tariff (REFIT) was developed by the National Electricity Regulator of South Africa (NERSA) [47] to support the introduction and development of renewable energy options in 2009. Phase I (until 2013) of the programme focused on wind, concentrated solar, land-fill gas and small hydro plants. Phase II (2013-2018) includes electricity from large-scale grid connected photovoltaic systems (>1 MW), biomass solids, biogas and concentrated solar power (CSP) with 6 hours per day storage. Data on feed-in tariffs are presented in Chapter 5.

Renewable energy, in general, has been recognised in the South African Integrated Energy Plan (IEP) [40, 41, 53]. The IEP provides a framework with which specific energy development decisions can be made. However, challenges remain for South Africa to fully engage in the use of renewable energy in general and bioenergy specifically. South Africa's heavy reliance on coal to meet its energy needs at low cost, i.e. for generation of most of the country's electricity and a significant proportion of its liquid fuels, pose challenges for the introduction of bioenergy.

South Africa has a vast commercially exploitable natural, agricultural and forestry resource [52, 50, 132, 133, 134, 135]. A detailed analysis of the types of biomass available in South Africa is provided in Chapter 4. Coal is a non-renewable energy source. Furthermore, South Africa's industry has not generally used the latest in energy-efficient technologies, mainly as a result of relatively low energy costs [53]. For that reason, South Africa has adopted, in its *White Paper on Energy Policy* [41], a strong position with respect to renewable energy based on the integrated resource planning criterion of:

> "*Ensuring that an equitable level of national resources is invested in renewable technologies, given their potential and compared to investments in other energy supply options.*"

The driving force for energy security through diversification of supply in South Africa has remained one of the *White Paper on Energy Policy's* key goals, since a major portion of the nation's expenditure is via dollar-denominated imported fuels, mainly fossil fuels, that impose a heavy burden on the economy. Furthermore, the South African economy, which is highly dependent on income generated from the production, processing, export and consumption of coal, is vulnerable to the possible climate change response measures being implemented or to be implemented by developed countries [41, 50, 115]. At the same time there are now increased opportunities for energy trade, which is built on:

> "*Given increased opportunities for energy trade, particularly within the Southern African region, Government will pursue energy security by encouraging diversity of both supply sources and primary energy carriers* [41]."

and

> "*Diversify energy supply by developing advanced, cleaner, more efficient, affordable and cost-effective energy technologies, including fossil fuel technologies and renewable energy technologies .... With a sense of urgency, substantially increase the global share of renewable energy sources with the objective of increasing its contribution to total energy supply, recognising the role of national and voluntary targets.*"[40]

Bioenergy resource development in South Africa is in a nascent stage, while competing fossil fuels are established and have relatively low costs, and are able to generate high returns [54, 40, 55]. South Africa developed a framework, the "Biofuels Industrial Strategy of the Republic of South Africa of 2005", adopted in 2007, within which the bioenergy industry can operate, grow and contribute positively to the South African economy and the global environment [40, 41, 50]. The biofuels strategy emphasises the need for entrepreneurship and innovativeness of South Africa's industrial and financial sectors; as well as the need for the South African Government to develop appropriate policies and frameworks that would encourage and guide the private sector, i.e. subsidies [53] to produce bioenergy.

Not all renewable energy targets for 2013 under the '*White Paper on the Energy Policy of the Republic of South Africa'* [41] and '*White Paper on Renewable Energy'* [40] were attained by 2013; especially the biofuels targets lag behind [56]. Authorities have subsequently adjusted the timelines and options specifically relating to bioenergy targets. To meet primary energy supply targets, new biomass options only feature when presented as relevant. Biomass energy options are gradually introduced into the energy mix until 2030, with a first timeline set for 2018 now [56]. The report published by the South African Government Gazette [56] states:

> "*While the actual realisation of this target has lagged behind, government remains committed to increasing the share of renewable energy with the total energy mix of the country.*"

According to a macro-economic study on utilising renewable energy resources in South Africa, electricity production from commercially based biomass is among the most effective for renewable energy applications [142]. Assuming a least-cost approach for implementation of renewable energy applications, a major contribution to the Renewable Energy Targets can be derived from commercially available biomass resources.

2.4 SECURITY OF SUPPLY, COSTING, MARKETS AND POLICY IN NAMIBIA

Namibian bulk energy suppliers do not use wood-based biomass as feedstock [18]. Nor is a policy or the legislation in place that would enable the use of biomass as a source of bulk energy supply to the Namibian economy. This is relevant for both power generation and solid or liquid fuel. Numerous studies have been conducted to establish whether biomass, especially wood-based biomass, could serve as a source of bulk energy supply [282, 265, 88, 102,]. The strategic plan [109, 116] to build an industry with the main focus on bioenergy production, was not considered by Government of the Republic of Namibia as yet.

2.5 MODELLING APPROACH

By analysing the South African national targets and policy decisions to deliver energy derived from biomass, new opportunities for bioenergy production were identified by this research, both in the Namibian and South African context. Figure 2-1 illustrates how the bioenergy production system could be drawn up, i.e. conceptualising policy guidelines on renewable energy targets by the production of bioenergy. The conceptual framework followed in this research proposes a downstream process flow (a value chain) from sourcing wood-based biomass materials to the marketable bioenergy product. The implementation of the conceptual framework should be kept dynamic; meaning that it is responsive to internal management measures and external factors; especially the external factors relate to:

- macroeconomic and fiscal development targets (Chapter 1);
- national policy directives on renewable energy targets (section 2.3);
- national social development challenges (Chapter 1);
- national and global environmental concerns (Chapter 1);
- availability of know-how and technological adaptability (Chapter 4, section 9.9);
- availability of national and international standards, and accompanying markets (Chapter 8, 9); and
- security of feedstock supply (Chapter 6).

The internal management measures relate to the core thermo-chemical conversion and business process flows itself, i.e. the effectiveness and efficiency to convert wood-based biomass via fast pyrolysis into economical viable bioenergy products. In particular the matters arising for internal process management include:

- feedstock types and supply systems (Chapter 4, 5, 6);
- fast pyrolysis process parameters (Chapter 7, 8);
- handling, storage, logistics of feedstock and products (Chapter 5, 8);
- types of products to be produced, including market sizing (Chapter 7, 8); and
- core process flow administration (Chapter 9, 9.9).

Figure 2-1 visualises the conceptual framework: the core process flow from supply of wood-based biomass to marketing of a bioenergy product; and how/where external factors can influence the internal management process. Chapter 4, 7, 8 and 9, describe the internal process based on the feedstock type that will be used and what properties these have; the fast pyrolysis conversion process and which products would be delivered in more detail. Section 2.3 and Chapter 9 discuss the economic viability of the overall process in the context of external factors.

For each of the steps indicated in Figure 2-1, literature was reviewed to build the necessary scenarios for a "bioenergy model" for Namibia and South Africa. By providing an overview the conceptual framework 'from biomass to product' it shows the steps that need to be followed to integrate bioenergy systems into a Southern African economy, and the external factors that may influence the process. That means, value can be added to the biomass (regardless whether virgin wood or waste/residual wood based materials) by putting the biomass through a thermo-chemical conversion process, thereby deriving new products which could be sold to various markets to gain benefits such as income or environmental sustainability. The feasibility and economic viability of the thermo-chemical conversion process, i.e. fast pyrolysis in this case, will be tested (Chapter 7, 8, 9).

The general concept proposed in this research further allows that the core process flow is influenced by external factors which make a process sustainable or render it unsustainable over the short or long term. The factors that influence sustainability consist of national policies and legislation, production parameters, product and market norms and standards. The structure of the conceptual framework incorporates both a long-run equilibrium based on theory and historical economic relationships, and short-run dynamics (e.g. shocks) that allow the production system to gravitate towards its long-run techno-economic equilibrium.

In proposing a conceptual framework, the development of a plausible model is required; a balance is needed between the desire to incorporate a large number of variables and equations in the model and to keep the overall structure relatively simple. The number of equations must be sufficient to generate estimates of key technical and economic variables and analyse production system developments; but at the same time the model needs to remain transparent and ensure simplicity of operation.

The modus operandi followed by this research is 'concept precedes model'. This chapter thus largely informs analyses (Chapter 4, 5, 7); modelling (Chapter 6, 8); and results (Chapter 9). These specifically draw down from the conceptual framework proposed as illustrated by Figure 2-1. The terms in the process flow, like biomass, gasification, reforming, pyrolysis, bio-oil, syngas, fuels and commodity chemicals are defined in Chapter 3. Related terms like the type of pyrolysis processes and pyroligneous liquids are also described in Chapter 3. The descriptive terms used in Figure 2-1, like benefits, costs, markets, shock and macroeconomic framework and/or policy interventions are described below.

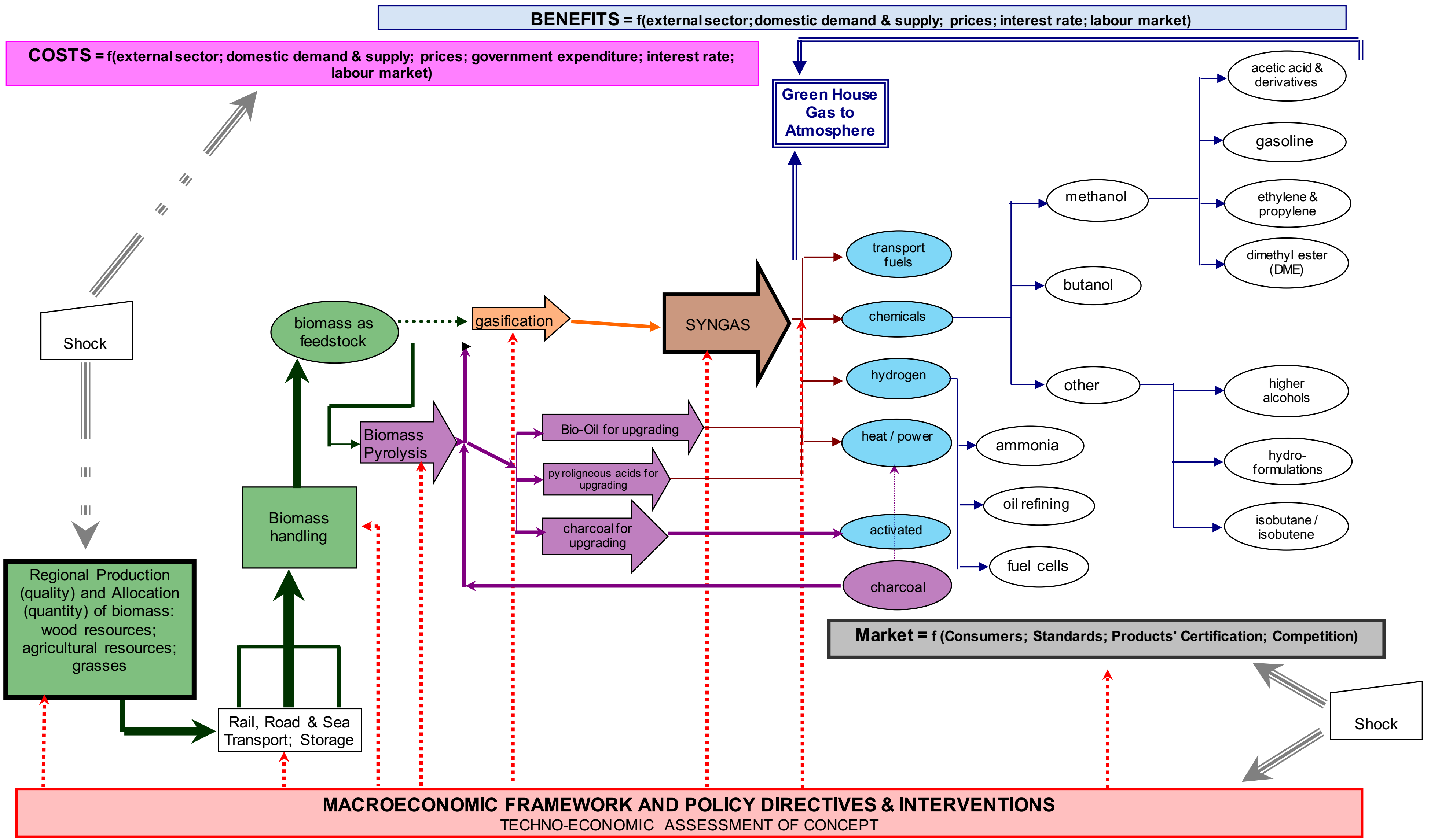

Figure 2-1 Relationship driven model for a fast pyrolysis ('wood to products') conversion process in Namibia and South Africa

2.5.1 Shock

Shocks are those dynamics that are externally induced but which may have grave influence on the core process flow. The nature and origin of shocks are diverse and span from climatic conditions, which may influence feedstock supply, to economic, which may influence overall sustainability of the production system. It is implicit that shocks are random and unpredictable and therefore impossible to model without some expression for risk or uncertainty. The possible effect that shocks can have on the suggested production system are modelled as part of sensitivity analysis (Chapter 8).

2.5.2 Costs and benefits

Costs are all direct and indirect costs related to the capacity of the production system. Direct costs include capital expenditure to set a production system up, and operational expenditure that maintains a production system. Direct costs are quantifiable and recurring. Indirect costs may relate to opportunity costs incurred due to insufficient production capacity, inferior quality of products and insufficient productivity or staffing, and potentially their insufficient skill. Indirect costs may also be induced by shocks and cannot always be quantified as they are generally occasional in nature. In a production system, costs cannot be avoided, but it is desirable to keep costs as low as possible and eliminate indirect costs. For this research, each phase of the core production system was costed.

Benefits are all gains derived from operating the proposed production system on a continuous basis and on cost sustainability, both environmentally and economically. Benefits related to the gains directly from the production system itself, and the benefits that the production system brings for the community in which it is built. Examples of benefits relate to the utilisation of wood-based biomass resources not used elsewhere, revenue generated, jobs created in a certain community and contribution to reaching national economic goals as, for example, discussed in sections 2.1 and 2.2.

2.5.3 Market

Market relates to the possibility to sell the products of the production system (in this research bioenergy), nationally, regionally (in the African context) and internationally. Products are produced to the norms, practice and standards (acceptance) of the markets and its consumers. Production systems and products are usually accredited to comply with the required norms and standards. Accreditation can be done nationally and internationally. Typical norms and standards relate to minimum requirements for quality of products, metrology and labelling aspects for packaging and environmentally considerate production systems.

2.5.4 Macroeconomic framework, international drivers and national policies

The macroeconomic framework of a country is informed by its socio-economic setting and international drivers. Generally, governments aim to develop national policies which address specific socio-economic issues to preserve a stable macroeconomic system, yet provide a government with revenue from taxes paid by profitable companies. In the case of Namibia and South Africa, security of energy supply and enhanced economic growth are key to maintain a stable macroeconomic system. Security of energy supply is a medium term macroeconomic goal. Sustained and high economic growth is a long term macroeconomic goal.

2.5.4.1 The Namibian macroeconomic framework, international drivers and national policies

Namibia's macro-economy is declared as stable and conducive towards private investments which assist the government to increase sustainable socio-economic growth [4, 15, 16, 22]. Policies or legislations governing the generation and transmission of energy from renewable sources do not exist [18]. However, the opportunity that lies in generating energy from renewable resources has been recognised by the Namibian government [57]. The Namibian government has appointed consultants from VTT Technical Research Centre Finland [58] to assist with the compilation of appropriate policies and legislation with specific guidelines on how renewable energy sources can be incorporated into the economic mainstream. Technical advisory work and a draft policy/legislative framework were advised in 2013, also based on the current power supply systems' regulations. The rationale for the report was to present a review of the now 15 year old energy policy, and includes:

- literature review on national documentation supporting energy systems, integration of renewable energy into the national energy mix, and energy efficiency
- current status of energy statistics
- energy systems modelling with current and future uses of energy, and possibilities to sustain supply for future uses, and
- recommendations on how to update the energy policy of Namibia.

In the current legislation, independent power production systems are acknowledged and allowable, both in urban and rural areas. Namibia is a member of the Southern Africa Power Pool (SAPP) which seeks to provide a harmonised system of public and independent power producers (IPPs) across the Southern African region; enabling Namibia to develop policies which are also in line with regional and international standards. A regulated and unified feed-in tariff system is the remaining challenge encountered by independent power producers [18]. Decentralised power production systems which use their generated power themselves are not affected by the lack of this regulatory framework.

2.5.4.2 The South African macroeconomic framework, international drivers and national policies

In South Africa a macroeconomic framework conducive to renewable energy generation is expressed by the objectives of the "Biofuels Industrial Strategy" (described in sections 1.3.3 and 2.3) [7]; policies to deploy renewable energy for electricity generation [40, 47] and the country's commitments towards sustainable development [240]. The biofuels strategy initially aims to develop the biofuels industry to achieve a market penetration of 2% of road transport liquid fuels by 2013. The biofuels strategy seems to target known/proven technologies like the production of bioethanol and biodiesel via biomass fermentation and digestion or trans-esterification routes respectively. The strategy proposes the use of agricultural produce or by-products, thus mostly first generation biofuels are promoted. Biofuels produced on the basis of maize are explicitly excluded: the prerequisite of the strategy is that a bio-based energy level of 2% penetration must be achieved without jeopardising food security [7, 53, 51, 148]. Crops like soya or sunflower are to be used instead, even if there is need to import these. The 2% penetration level of biofuels in the national liquid fuel supply chain represents 400Ml per annum. The policy to integrate renewable energies into the power generation cycle by also providing guaranteed feed-in tariffs (phase I, until 2013) in South Africa since 2009 has accumulated more than 1.1MW power capacity [47], built through independent power producers (IPP).

The potential of using wood-based biomass to contribute to the attainment of this goal is not explicitly mentioned but also not explicitly excluded from the strategy. Neither does the strategy prescribe the kind of technologies to be used for the attainment of these targets. This research thus implicitly accepts that other, alternative technologies which render equivalent results (bio-based liquid fuels or power) can be used. In the South African context, the conceptual framework draws upon the biofuels strategy to fulfil national macroeconomic targets (lower bar in Figure 2-1). Using wood-based biomass resources as proposed in this research to produce energy does not jeopardise food security. Equally important: this research does not propose that food producing land is to be transferred to biomass producing land for energy. Harvesting of wood-based material should also not cause deforestation. In terms of the "*first and second economy trajectory*", the South African Government intends to support the development of underutilised land to a level at which those affected communities will be able to compete commercially (subsistence farms should be converted to higher productivity farms). Farmers located in underdeveloped land areas will be encouraged through cooperatives (where feasible and possible) to participate in the supplying feedstock to biofuel "refineries" [7, 30]. In terms of supply of wood-based biomass as feedstock to the core production system, this research considers the possibility of sourcing wood-based biomass from underutilised land, and thereby participating in biofuel supply.

The biofuels strategy foresees that producer (or investors') incentives should only be allocated to projects that involve expansion that assist in achieving the 2% target. This is seen to ensure job creation, expanded agricultural production, and increased food supply; also contributing to technological feasibility and economic viability through direct and indirect benefits of using bioenergy.

Macroeconomic policy furthermore requires interactions and active engagement with stakeholders and joint decision making between the private and public sectors. Thereby, socio-economy (empirical macro- & micro- economics, research, bioenergy modelling, institutional & experimental economics, indigenous knowledge) and environmental aspects are linked. The conceptual framework takes account of these events, as summarised in the 'assessment' and 'interventions' part of the macro-economic framework bar of Figure 2-1.

2.6 THE CONCEPTUAL MODEL DERIVED FROM THE CONCEPTUAL FRAMEWORK

The conceptual model, i.e. modelling bioenergy production both in Namibia and South Africa is based on the conceptual framework as visualised by Figure 2-1. The overall conceptual model is built by modelling each stage of wood-based biomass transformation up to delivery of the bioenergy product. The specific models derived and used in this work are listed in Table 2-1. Details of the models developed and the relevant literature are also provided in sections 4.1, 4.2 and 4.5.

Table 2-1 Summary of model structure

Model Structure	Core Model
Biomass resources (supply side)	Wood-based biomass production function model used to determine potential growth over the forecast horizon of 20 years. This period is chosen to coincide with the technical lifespan of equipment, typical loan repayment periods, and taxation policy applied in Namibia and South Africa. This limited planning horizon did not intend to limit biomass supply sustainability, but ease modelling of technical feasibility and economic viability. It is acknowledged that this planning horizon may be too short to consider all effects of biomass growth and re-growth, but is realistic for technical and financial planning purposes. The wood-based biomass resources which received specific attention are Namibian bush encroachment, and in South Africa - commercial plantation forests (pine, eucalyptus and wattle) and bamboo. Details are provided in Chapter 4, 5, 6.
Fast pyrolysis (technical assessment)	Modelled according to the experimental work which was carried out with selected wood-based biomass resources. The yields and production parameters derived from experimental work are used as a proxy to model commercial scale fast pyrolysis production systems, where the feedstock is used as determined by the 'biomass resources model'. Replication is done for fast pyrolysis. As the Namibian and South African economies are inter-twined it is considered sufficient that replication of pyrolysis production system modelling is done based on biomass resources available, and not on a country specific basis. Details are provided in Chapter 5, 7 and 8.
Cost and Benefits (socio-economic and techno-economic assessment)	Modelled to reflect costs and benefits of the fast pyrolysis production systems. This model draws upon the results of the fast pyrolysis model, and takes the economic indicators of Namibia and South Africa into account respectively, like factors of production (biomass resources and feedstock preparation, labour, land, cost of credit) and inflation. Costs incurred by establishing a fast pyrolysis production system are offset against the benefits derived (e.g. jobs created, agricultural land recovered, additional energy supplied). Exogenous and endogenous economic factors are considered. The difference between costs and benefits determines the net sustainability of a fast pyrolysis production system in the Namibian or South African context. The assessment horizon spans over a 20 year horizon to ease modelling. Results are provided in Chapter 9.
Market and Market opportunities (demand side)	Modelled according to national accounts of Namibia and South Africa respectively, and key data / indicators from markets like Europe: indicators for each product type include spot consumption and trends of consumption, imports and exports. Other factors of importance, which are considered but not modelled, are norms and standards for products to be delivered; production standard requirements to fulfil international commitments and acceptance norms; competitiveness of the products nationally and internationally. This model 'ties' the latter three core models together, as is the ultimate opportunity that determines whether a production system is viable and/or sustainable. Results are provided in Chapter 9.

Model Structure	Core Model
Data validation and sensitivity analysis	A large battery of diagnostic tests were performed on data and equations. These diagnostic tests included tests to evaluate the distribution of the residual values, validate coefficient restrictions, assess parameter stability and to identify structural breaks. Stationarity and co-integration tests were also performed. A definition of stationarity is given in section 3.5.1.

Following each modelling step, conclusions and recommendations are provided to establish the rationale for the next modelling step.

3 DEFINITIONS AND DESCRIPTION OF TERMS; APPLICATION OF THERMO-CHEMICAL TECHNOLOGY IN SOUTHERN AFRICA

This chapter provides definitions of the terms used in this research. The definitions are presented in line with the process flow as explained in the conceptual framework described in Chapter 2.

Additional definitions are provided to further enhance the understanding of Namibia's and South Africa's socio-economic development context. All of the research is carried out in the context of Namibia and South Africa unless otherwise specified.

3.1 BIOMASS

Biomass refers to plant matter, which is renewable in the short term. Biomass feedstock to produce biofuels include the following – waste materials (agricultural, wood, and urban wastes, crop residues); forest products (wood, logging residues, trees, shrubs, mechanical conversion by-products), energy crops (starch crops such as corn, wheat, barley, sugar crops, grasses, vegetable oils, hydrocarbon plants), or aquatic biomass (algae, water weed, water hyacinth). Biomass can be used to produce heat, make liquid fuels, gas or chemicals, and/or to generate electricity.

For this research, only wood-based biomass was considered and specifically wood-based biomass material which is derived from trees, bush and shrubs in Namibia and South Africa, i.e. draws away from resources that could otherwise ensure and/or sustain food security. Under Namibian conditions, the focus is on invader or encroachment bush. Under South African conditions, the focus was on wood-based biomass from commercial forestry production systems, invader or bush encroachment in savannah areas and invasive alien tree, bush and shrub species. Only certain wood-based biomass resources were analysed as data on these are available in Namibia and South Africa. In addition, it was found that other biomass resources are available, but not in the abundance necessary to consider further analysis from a technological and economic perspective. Selected wood-based biomass was experimentally evaluated for its potential use in fast pyrolysis processes.

This research acknowledges that when dealing with wood-based biomass it is likely that the feedstock material may not be chemically consistent, mainly because of the differences in softwood and hardwood species. But also because of the geographic location and soil conditions where these grew, and the moisture content in the biomass material at the time it would be converted. Care should therefore be taken in selecting a biomass feedstock since its characteristics vary not only from species to species, but also from tree to tree (or shrub or bush), the parts of the tree, shrub or bush to be utilised in the conversion process and also regions within the tree, shrub or bush. In conversion processes, the most significant differences are the parts of the tree, shrub or bush to be utilised, i.e. only wooded parts, whether it is a hardwood or softwood species to be used, and the moisture content of the biomass at the point of conversion. The latter aspects significantly influence fast pyrolysis product quality and yield. The practical implications on the fast pyrolysis conversion process of other biomass characteristics are technologically negligible. The wood types used in this research are discussed in Chapter 5, 6 and 7.

Wood is made up of cells, which are laid down successively on the outside of the stem as the tree/bush/shrub grows. On the outside of the tree is a layer of bark. The proportion of the bark relative to the inner wood parts differs substantially if comparing trees, shrubs and bush. The highest proportion of bark is found in shrubs due to the proportionately high amount of branches and twigs. Bark can be further subdivided into an outside layer of dead cells and an inner layer, which contains living cells. In between the bark and the wood is a layer of cambial cells, which subdivide during growth to form both wood and bark cells. The activity of the cambial zone is greater at certain times of the year (spring). During this time springwood (early wood) is laid down and as the season progresses summerwood (latewood) is laid down. Spring and summerwood have different chemical compositions and colourings and so are easily distinguishable, which accounts for formation of growth rings [59]. Although the formation of growth rings is different from year to year, this aspect will not be considered for the purposes of this research as it is beyond its scope; and technologically does not influence fast pyrolysis product yield and quality. It is also recognised that wood and bark have different physical and chemical properties. Biomass from trees, shrubs and bush used in this research are considered as a unit and are not thermo-chemically converted separately. This is because this research sought to establish the usefulness of the wood-based resource under the whole-tree-utilisation method to generate bioenergy. Debarking wood is an interesting pretreatment option to improve fast pyrolysis products yields, especially bio-oil and quality. For wood-based biomass considered in this research, debarking was not necessary. Bark on *Acacia*-bush, wattle and *Eucalyptus* loosens shortly after felling and falls off readily.

Trees, bush and shrubs are classified into two groups, angiosperma (hardwoods) and gymnosperma (softwoods). Hardwood species usually have broad leaves and are deciduous in the temperate zone. Softwood species usually have needles, produce seed cones and are often coniferous or evergreen.

It is not the aim of this research to explain the wood-based biomass' physical and chemical properties in detail. Rather, detail is presented on

- the occurrence of hardwood and softwood in the Namibian and South African context, and
- the chemical properties of the wood species for their usefulness to bioenergy generation via fast pyrolysis.

The latter is presented in Chapter 7.

3.1.1 Specific wood-based biomass resources investigated

'Bush-encroachers' or 'bush encroachment' or 'invader bush' refers to indigenous tree and shrub species that grow where they are not wanted. Many indigenous dominant woody species in Namibia and South Africa are termed encroachers as they invade specific areas or locations such as overgrazed land and wastelands. Bush encroachers as a biomass resource is described in sections 6.1 and 6.2.3.

'Invasive alien plant species' refers to plants which are not indigenous to Namibia or South Africa. South Africa aims to eradicate or at least substantially contain alien plant species to specific areas and for specific industrial use. For example, all tree species in plantation forests are declared alien plant species, including species like *Pinus* spp. (commonly referred to as pine), *Eucalyptus* spp. and *Acacia mearnsii* (commonly referred to as black wattle or wattle). South Africa's aim is to contain the growth of these plants to commercial forestry. Planting of pine, eucalyptus and black wattle outside demarcated commercial forest plantations is prohibited by law [60]. One type of softwood (bamboo) and three hardwood species (*Eucalyptus* spp., Wattle, Encroachment Bush, mainly *Acacia* spp.) were experimentally analysed for the purposes of this work. The quality and yield from fast pyrolysis conversion are presented in Chapter 7.

3.2 THERMO-CHEMICAL CONVERSION TECHNOLOGY

This section also provides a chronology on how pyrolysis technology was developed and used in Namibia and South Africa. The aim of presenting a pyrolysis chronology is to provide a better overview on why this research considered introducing fast pyrolysis to Namibia and South Africa as may be feasible and viable as a technological option in the socio-economic development context. The discussions are presented in Chapters 7, 8 and 9.

3.2.1 Fast and slow pyrolysis

Pyrolysis is the thermal decomposition of materials in the absence of oxygen or when significantly less oxygen is present than required for complete combustion [8, 61, 62, 70, 68, 74]. Pyrolysis processes have been improved and are now widely used for carbonised coal or for deposits left on catalysts, and charcoal production. Pyrolysis dates back to at least ancient Egyptian times, when tar for caulking boats and certain embalming agents were made by pyrolysis [63, 182]. In literature older than 30 years, pyrolysis generally refers to carbonisation, in which the main product is a solid char [64, 65, 70]. Carbonisation covers slow pyrolysis. Today, the term fast pyrolysis usually describes processes in which pyrolytic oils, commonly referred to as bio-oil with well-defined characteristics (Table 3-1), is the dominant product [63, 66]. Particle size, process time and temperature are used to mainly determine whether a thermo-chemical process is slow, intermediate or fast pyrolysis. The pyrolysis of a solid biomass particle can be divided into six primary physical processes [61, 67]:

a) heat transfer from a heat source to the particle, to increase temperature inside the particle;
b) secondary solid/liquid phase reactions - the initiation of primary pyrolysis reactions at temperatures higher than 100ºC releases volatiles and forms char;
c) gas phase reactions (flow of hot volatiles) both internal and external to the particle;
d) gas and liquid phase diffusion and/or convection within the particle – condensation of some volatiles that can produce tar;
e) mass transfer with the surroundings - autocatalytic secondary pyrolysis reactions proceed while primary reactions (item b. above) simultaneously occur in competition; and
f) heat transfer with the surrounding - further thermal decomposition, reforming, water gas shift reactions, radicals’ combination, and dehydrations can also occur, which are a function of the process’ residence time/ temperature/ pressure profile.

For the classification of pyrolysis technology, this research differentiated between traditional batch charcoal making (small scale kiln technology where the product is less than 1t per charring process; and one charring process takes between 36 to 48 hours) and the industrial processes for slow pyrolysis processes which use large scale kiln and retort systems. Fast pyrolysis processes use systems of continuous raw material (feedstock) and product flow. There are at least six variations of pyrolysis summarised in Table 3-1. Three products are always produced; the proportions can be controlled by the process.

Table 3-1 Pyrolysis modes [8]

Mode	Conditions	Liquid	Char	Gas
			wt% products	
Fast	~500ºC; short HVRT ~1s; short solids RT	75%	12%	13%
Intermediate	~500ºC; short HVRT ~10-30s; moderate solids RT	25% oil 25% water	25%	25%
Slow	~400ºC; long HVRT; very long solids RT	35%	35%	30%
Torrefaction	~300ºC; long HVRT; long solids RT	Vapours	85% solid	15% vapours
Gasification	~800-900ºC; short HVRT; short solids RT	1-5%	<1%	95-99%
Hydropyrolysis	~400ºC; pressure; hydrogen; possible catalysts	20-30%	40%	30-40%
	HVRT = hot vapour retention/residence time RT = retention/residence time			

The products from slow pyrolysis can be used in a variety of ways. The char can be upgraded to activated carbon, used in metallurgical industry as a reduction agent, as a domestic cooking fuel or for barbecuing. Fast pyrolysis produces mainly bio-oil as product, and the char is, for example, completely consumed in Ensyn and BTG type of fast pyrolysis processes (section 3.2.1.1). Pyrolysis gas can be used for power generation or heat, or after cleaning, can be synthesised to e.g. methanol or ammonia. The liquid, pyrolysis oil (a phase-separated liquid from a slow pyrolysis process) or bio-oil (usually a single phase liquid from a fast pyrolysis process) can be upgraded to hydrocarbon liquid fuels for e.g. combustion engines, for extraction of valuable chemicals or chemical compounds (e.g. aldehyde, phenols, alcohols, furans, etc.), or used directly as fuel for power generation or heat (by combustion). Bio-oil for fuel purposes were considered only.

Fast pyrolysis is studied to analyse and evaluate the bioenergy opportunities and possible environmental impact in the Namibian and South African context. Also the various products derived from wood-based biomass conversion via fast pyrolysis were assessed techno- and socio-economically to establish their feasibility and viability in the local markets or for export elsewhere, notably Europe.

3.2.1.1 Fast pyrolysis

Fast pyrolysis of biomass feedstock gives high yields of liquids (bio-oil). It is characterised by rapid heating of the biomass particles and a short hot vapour residence time (HVRT) of product vapours (0.5 to 2 s). Rapid heating means that the biomass must be ground into fine particles (up to max. 5 mm in diameter) to guarantee rapid transfer of heat to the biomass particle and that the insulating char layer that forms at the surface of the reacting particles must be continuously removed in certain fast pyrolysis processes, except in fluid bed fast pyrolysis. Fast pyrolysis has a lower capital cost than liquefaction, and several fast pyrolysis technologies are currently being used commercially, including Dynamotive in Canada [29, 68], BTG in the Netherlands [29, 68], Ensyn in the USA [29, 68], METSO Corporation and Fortum in Finland [29, 68], and others in South America [29, 68]. Enecon in Australia [29, 68] are considering commercially-sized technologies. The main product from these commercial fast pyrolysis applications is bio-oil for energy production.

Existing examples of fast pyrolysis in Namibia and South Africa are not known. In South Africa one manufacturer of fast pyrolysis equipment exists, i.e. Prestige Thermal Equipment [69], however the technology is said not to be engaged in that country.

3.2.1.2 Slow pyrolysis or carbonisation

As explained before, literature generally equates slow pyrolysis to carbonisation or charcoal making, in which the principal product is a solid char [318]. Slow pyrolysis of biomass feedstock takes place when the organic matter is raised to a high temperature, i.e. above at least 180°C under exclusion of oxygen (retort processes) or under controlled air intake (kiln processes). Once the carbonisation process has entered the exothermic phase, no more outside heating is required and the temperature in a retort will climb slowly to its maximum of between 400° and 450°C. In a kiln process, the carbonisation process is halted after extinguishing the process, by stopping oxygen ingress; only heat is transferred for a predetermined time thereafter. Feedstock sizes vary from wood chips (25 mm in diameter) to logs (up to 250 mm in diameter and up to 2400 mm length). Processing time varies from several hours (continuous retort processes) up to seven days (kiln processes). The main product of a slow pyrolysis process is charcoal, and depending on the retort-type process used, tarry liquids and gases can be recovered for other uses including feeder gas for power production [62, 70]. In Namibia, health and safety problems with kiln type application were reported, i.e. imposing a major health hazard for persons operating the kilns due to heavy smoke emissions; and veld fires due to incomplete processes where the half-charred wood self-ignites as soon as the kilns are opened thereby setting the surrounding grass and brushes alight [71].

Several manufacturers of slow pyrolysis equipment exist in Namibia and South Africa, mainly manufacturing kiln equipment. Manufacturers and users of slow pyrolysis equipment, based on retort processes, exist in South Africa only. Although being technologically more advanced than kilns for charcoal making, the use of retort processes in Namibia stopped in the mid-1990. The reasons for the latter could not be established.

3.2.1.2.1 Kiln technology

Kiln technology means all equipment producing charcoal as the main product without the possibility to recover producer or converter gas. Gases and smoke are emitted to the atmosphere during the process. Reference to kiln technology is specifically made in this research to evaluate the development of the charcoal making industry; and as part of 'mapping' the road ahead for a bioenergy industry based on fast pyrolysis.

In Namibia, the 'Namibian Bush Drum' kiln is used to make charcoal. This Namibian 'invention' is the preferred technology since mid-1990s used by charcoal makers since it is unsophisticated, labour intensive, cheap, requires limited skills and can be transported on a wheel-barrow from one production site to another. Further details are provided in Table 4-6. Photographs of charcoal making with the 'Namibian Bush Drum' kiln are provided after Table 4-6.

In South Africa, the Brazilian Beehive Brick kiln and the Armco-Robson kiln are commonly used, with the Armco-Robson kiln being the preferred option for manufacturing charcoal. Further details on operations of Armco-Robson kilns are provided in Table 4-6. Photographs of charcoal manufacturing operations in South Africa are provided after Table 4-6.

The charcoal from kilns is of acceptable European standard, and is exported to Europe for barbecuing; various companies are certified under the "Forest Stewardship Council's (FSC)" label. The FSC label is advantageous to have if the barbecue charcoal is envisaged to be sold in retail outlets across Europe, notably the UK. The drawback of employing kiln technology lies in its low wood-to-charcoal conversion efficiency. To produce one tonne of charcoal requires between seven to eleven tonnes of wood, depending on the moisture content of the wood. Further comparisons to slow and fast pyrolysis technologies are provided in Table 4-6.

3.2.1.2.2 Slow pyrolysis retort technology

Slow pyrolysis retorts or converters are essential elements of the industrial plant, capable of recovering and refining charcoal co- and by-products in commercial grades and quantities. The products obtained from a retort system are present in an approximate ratio of 35% charcoal, 35% condensed liquids and 30% incondensable gases. Carbonisation in a retort allows for an integrated utilisation of the energy contained in the raw materials at an optimum level by utilising the incondensable gases as source of energy to sustain the carbonisation process. The quality of the charcoal of a retort process is usually superior to the charcoal obtained from a kiln process in terms of; charcoal sizes, ash content, volatile content and chemical structure of the charcoal [62, 64, 70]. The condensed liquids in retort systems are the main product and the charcoal is the co-product in terms of its value [70, 200]. Further details are provided in sections 3.3.3 and 4.5.1.2 which discusses the markets for wood tar and pyroligneous acid produced during slow pyrolysis. In South Africa only one type of slow pyrolysis retort process manufacturer is still operational; the CG2000 slow pyrolysis retort (Photographs after Table 4-6). The slow pyrolysis retort technology 'AGODA' ceased to be built and operated in Namibia and South Africa in the early 2000s.

3.3 PRIMARY PRODUCTS

The pyrolysis of wood produces a large number of products and chemical substances. Some of the products and chemicals can be used as supplements and/or substitutes for conventional fuels currently utilised in Namibia and South Africa, or even exported. Below a number of the primary products from pyrolysis are described in more detail.

3.3.1 Process gas from fast and slow pyrolysis processes

This is the gas that leaves the thermo-chemical converter (fast pyrolysis converter, retort or kiln), frequently also called 'off-gas'. In the fast pyrolysis process and, for example, in the AGODA retort process this gas would be used on-plant to sustain the thermo-chemical conversion process and not used commercially. A distinction is made between two types of off-gas which have different potential commercial values:

- Off-gas that is not passed through a scrubber, chiller or condenser system. It contains the pyrolysis oil vapours which cannot be chilled sufficiently quickly in the conversion process and is thus often referred to as the high calorific value gas. This gas is mostly re-used in the process for heating in slow pyrolysis.
- The residual gas which has passed through a scrubber, chiller or condenser system and has been stripped of the pyrolysis vapours. It is often referred to as "low calorific value or lean" gas, meaning that it is a heating gas of poor calorific value. It is composed of mostly CO, CO_2, hydrocarbons, nitrogen and water vapour. The residual gas is from both fast and slow pyrolysis.

3.3.2 Charcoal

Charcoal is the solid residue with high fixed carbon content from a fast and slow pyrolysis process. The majority of the charcoal remains in the slow pyrolysis converter. In slow pyrolysis processes charcoal is the main product and is used commercially. However, depending on viability, pyrolytic liquids from slow pyrolysis may be of equal or higher value than the charcoal made in the same process (e.g. Reichert slow pyrolysis retort system used in Germany; section 4.5.1.2). In fast pyrolysis processes charcoal is a by-product with little commercial value, mainly due to its very small size and relative quantity. Usually charcoal from fast pyrolysis processes is used on-plant as fuel; the char is consumed in the process by complete combustion, e.g. the ENSYN and BTG technology.

3.3.3 Slow pyrolysis oils with high tar content – "wood tar"

The pyroligneous liquids or pyrolysis oils from slow pyrolysis are constituted of water, heavier tar oils, lighter tar oils and light condensable organics, like acetic acid, methanol and other acids. These phase separate.

This wood tar is the pyrolysis liquids component derived from condensation of vapours from a retort slow pyrolysis process which was described in section 3.2.1.2.2. The viscosity and chemical composition of the pyrolysis oils largely depends on the number or type of condensation facilities available to the process. In general, the most significant problems of pyrolysis oils as a fuel are poor volatility, high viscosity, coking, corrosiveness, and cold flow problems, which can be overcome by, for example, catalytic upgrading [72].

Pyroligneous acid is a product of slow pyrolysis (section 3.2.1.2.2.) formed from condensable vapours [73, 62, 64, 70] and is the aqueous fraction of slow pyrolysis liquids. It is made up of moisture, acetic acid, wood spirit and light oils. The quantity produced or yield of pyroligneous acids depends upon the composition of the biomass and the conditions under which pyrolysis occurs.

3.3.4 Bio-oil

This is derived from condensation of vapours from fast pyrolysis which was described in section 3.2.1.1. Fast pyrolysis liquids are dark brown and fluid, resembling a medium fuel oil in viscosity. The liquid is often referred to as bio-oil or bio-crude although it will not mix with any hydrocarbon liquids. Bio-oil is also sensitive to high temperatures when it undergoes chemical change so it cannot be distilled. It has a higher heating value of about 17 MJ/kg, as compared to conventional fuel oil [68, 74] of typically 40-45 MJ/kg.

Bio-oil can be a substitute for fuel oil or diesel in many static applications including boilers, furnaces, internal combustion engines and turbines [68, 74, 75, 76]. There are a range of chemicals that can be extracted or derived including food flavourings, specialities, resins, agri-chemicals, fertilisers, and emissions control agents [67, 29, 68].

The specific use of bio-oil as a fuel requires adaptations of engines or gas turbines to suite bio-oil characteristics [8, 29, 68, 75]. And, after upgrading and modification of the physiochemical properties of the bio-oil it can be used as an alternative to diesel [29, 68]. Only the use of bio-oil as energy carrier is discussed in this research.

3.4 TERMS USED TO DESCRIBE THE SPECIFIC SOCIO-ECONOMIC SETTING IN NAMIBIA AND SOUTH AFRICA

This section explains the terms commonly used in the Namibian and South African techno-economic, social and scientific environment. For example, terms in the agricultural and forestry sectors in Namibia and South Africa differ from those used in developed countries, and are often unique and therefore require explanation.

3.4.1 Agricultural farmland

In Namibia, demarcation of land for extensive agricultural production systems, crop and livestock farming in commercial and communal farming areas (sections 3.4.2 and 3.4.3) measures 68.74Mha, including smaller towns and villages, and are divided into over 100 constituencies and combined to form some 20 districts. Here, analysis stop at the level of districts. The latter excludes protected by law land areas and national parks. The land available for agricultural production systems, excluding towns and villages measures 65.41Mha. Of the latter demarcated land, 51.72Mha is used predominantly for extensive livestock production systems, including domesticated (cattle, sheep, goats, horses, donkeys) and wild animals (game farming and hunting adventures).

3.4.2 Commercial Farmland / Commercial Farming Areas

These are defined as freehold, agriculturally productive land, dedicated to livestock rearing and/or game farming and/or cropping as per the Agricultural (Commercial) Land Reform Act [77]. Ownership, private or corporate, is registered with the Deeds Office, Ministry of Land Reform. The term ‘commercial farmland’ is used in the Namibian context only.

Access to bush or other wood-based biomass resources for fast pyrolysis has to be gained through owners of commercial farmland. Commercial farmers are key to security of supply of wood-based biomass as feedstock for fast pyrolysis.

3.4.3 Communal Land / Communal Farmland / Communal Farming Areas

Is defined as non-freehold land, dedicated to a specific community for livestock rearing and/or cropping as per Communal Land Act [78]. No ownership, neither private nor corporate, is possible to be registered. Only a permission to occupy and utilise can be registered with the Ministry of Land Reform. The specific community's approval, via a traditional authority, must precede a permission to occupy/utilise licence. Fencing off any specific area in communal land is considered illegal. Demarcated and proclaimed urban areas situated in communal land areas are excluded from this arrangement. The term 'communal land' is used in the Namibian context only.

Access to bush or other wood-based biomass resources for fast pyrolysis has to be gained through the traditional authority that manages a certain area in the communal land. Traditional authorities are key to the security of supply of wood-based biomass.

3.4.4 Bush Encroachment

Bush encroachment refers to the phenomenon where a large number of invasive wooded plant species are spread over large geographic areas, usually more than several hectares (section 3.1.1). Bush encroachment is *a priori* defined as the total number of bushes (measured in TE-units/ha) that exceed 2,500 per hectare [79, 80, 88, 262, 93, 265].

Bush and trees from encroached areas were considered to be a renewable wood-based biomass resource to be used as feedstock for fast pyrolysis and therefore possible inventory levels, mean annual increments and environmentally and economically sustainable usage were modelled. Of the 51.72Mha of demarcated livestock farming area, it is estimated that 26Mha were bush encroached [262] in 2002, with an increasing tendency and said to have reached some 30Mha in 2012 [81]. One of the aims of the national rangeland management policy and strategy [81] are to reduce bush encroachment to improve rangeland quality and grow livestock production output. In the Namibian context, encroacher bush is the only wood-based biomass resource that was considered for fast pyrolysis conversion.

In the South African context, encroachers from indigenous bush or tree species are one of four possible wood-based biomass resources that could be used for fast pyrolysis conversion processes. The total area said to be encroached by indigenous bush and tree species covers an area of 29Mha across South Africa as per FAO reports [121, 122]; of this area some 10-20Mha are said to be very densely bush encroached [160] and affecting agricultural productivity and biodiversity. Judging by these FAO reports, the area encroached by indigenous wood species in South Africa has remained more or less constant.

3.4.5 Tree Equivalent Unit (TE-unit)

Unlike commercial forestry where the standing density and potential yield of a forest can be determined by a set of formulae for a specific species, the standing density and potential yield of bush encroachment cannot be easily determined. The concept of 'tree equivalent unit' was developed to provide an estimation of the standing density and potential yield of bush in Namibia and South Africa.

A tree equivalent unit measures the stem size of a shrub or bush which is 1.5m tall, and has a diameter of between 100 and 150mm at knee-height. Therefore, e.g. a bush with a stem of 3m height and a diameter of 150mm at knee height would count for 2 tree equivalent (TE) units [82, 96]. Bushes are usually multi-stemmed and each stem's TE-unit would have to be determined to calculate the total amount of TE-units per hectare (TE/ha). Typically, a bush consists of at least three stems; it should therefore be determined what is each stem's diameter and height as per afore mentioned.

Although no conclusive research was done [262], the size of a Namibian bush is defined as TE-units and the weight of one TE-unit was established to be between 2-18kg, depending on the species (section 5.1.1). All units of measure, including TE-units, were converted to Mt equivalent to ease modelling.

3.4.6 Carrying Capacity (CC)

Carrying capacity is defined as the ability or capability of a hectare of demarcated agricultural land, both commercial and communal, designated for livestock rearing to bear a certain amount of live body mass of domesticated and/or wild animals from which income can be generated in some point in the future. Carrying capacity is made up of browse capacity (i.e. the amount of nutritionally valuable fodder, predominantly leaves and twigs delivered by trees and bushes) and grazing capacity (i.e. the amount of fodder delivered by grass). Carrying capacity is usually expressed as the ability to bear a certain amount of live body mass (kg livestock and/or game) per ha, thus (kg/ha). In this research, the term 'carrying capacity' is predominantly used where bush encroachment inhibits livestock productivity (Namibia) or biodiversity (South Africa). Bush encroachment is said to negatively impact on carrying capacity of farmland due to imbalances of browse and grazing capacity. However, the dynamics between bush encroachment and carrying capacity are not sufficiently documented to provide an indication if bush encroachment adversely impacts on farmland carrying capacity. This research assumed that benefits towards enhanced livestock productivity and biodiversity are gained if bush encroachment decreased. Data on the current status of carrying capacity in Namibia is provided in Chapter 5. Modelling biomass resources (Chapter 6) could provide an indication on how carrying capacity changes with lessening bush encroachment.

3.4.7 Livestock

Here livestock refers to animals which are valuable for extensive production systems, i.e. animals are free-roaming/free-ranging, not kept in pens and not fed, in the Namibian context. The livestock considered include domesticated animals like cattle, small livestock (sheep, goats), horses, donkeys; and non-domesticated animals with commercial value such as browsers and zebras. Browsers are various types of game, predominantly antelope, which share agricultural farmland with domesticated livestock. For calculation purposes units used to express the total amount of livestock on demarcated agricultural land are million tons (Mt) live weight or "cattle equivalent" or "large stock unit - LSU". The following conversion factors were used to express "cattle equivalent" body mass:

3.4.7.1 Large Stock Unit (LSU)

LSU refers to cattle in a commercial and/or communal farming set-up. The basis to measure the live body mass of livestock is cattle, and expressed as "large livestock unit (LSU), whereby 1 LSU = 338 kg live mass. This mass was calculated from the weighted average livestock production figures for the years 1970 to 2013, including adults and calves or foals. For periods prior to 1970, figures of livestock production were provided in an infrequent manner. Ownership of large livestock is clearly identifiable via branding marks and ear tags registered at the Meat Board of Namibia. LSU size, as mentioned herewith, pertains to Namibian conditions only. LSU is converted to Mt equivalent in all calculations. Other livestock considered include horses and donkeys, browsers (i.e. antelope) and zebra; whereby

1 LSU = Cattle = 338kg live body mass

1 Horse or donkey = 1.5 x LSU ≡ 507kg live body mass; this measure is determined *a priori.*

1 Antelope = 3/4 LSU ≡ 254kg live body mass [83, 84].

1 Zebra = 1.4 LSU ≡ 473kg live body mass [83, 84].

Please note, the measure for LSU may change over time as it is based on livestock production output which itself changes over time. The Namibian livestock production system is influenced by multiple factors, like: farm management; climate and annual precipitation; palatable forage in the extensive livestock production system.

3.4.7.2 Small Stock Unit (SSU)

SSU refer to goats and sheep in a commercial and/or communal farming set-up. Ownership is clearly identifiable via tattoos in ears and/or ear tags. Ownership is registered at the Meat Board of Namibia or the Directorate of Veterinary Services, Ministry of Agriculture, Water and Forestry, Namibia. SSU size, as mentioned herewith, pertains to Namibian conditions only:

Whereby,

1 SSU = 1/6 LSU ≡ 56kg live body mass [85, 86];

3.5 TERMS USED TO DESCRIBE MATHEMATICAL, ECONOMICAL AND STATISTICAL CONCEPTS USED IN THIS WORK

3.5.1 Stationarity of data

A stationary process has the property that the mean, variance and autocorrelation structure do not change over time [87]. Stationarity can be defined in precise mathematical terms, but for the purpose of this research, it means a flat looking series, without trend, constant variance over time, a constant autocorrelation structure over time and no periodic fluctuations (seasonality) or infinite shocks (section 2.5.1). That means a stationary data series returns to a fixed value or fluctuates around a linear trend. A test for stationarity of data series (using Dickey-Fuller and/or Augmented Dickey-Fuller Test and/or autocorrelation function) is established prior to any further analysis of data; because if the data is stationary then many simplifying assumptions can be made. Testing for stationarity is solved in EViews®8. The data series available to this research for South African commercial forestry residues and invasive alien wood based biomass is stationary (sections 4.1.3.2 and 4.1.5).

3.5.2 Cointegration

Cointegration is the existence of a common trend or the existence of a cointegrating relationship. In this research, cointegration was tested throughout time series analysis for the determination of future available wood-based resources in both Namibia and South Africa.Cointegration was expressed by the significance of an independent variable (regressor) on the dependent variable. For example, section 6.1 established how and if annual precipitation and livestock production have influenced bush encroachment in Namibia from 1957 to 2013.

4 REVIEW OF LITERATURE AND MODELS

This chapter covers a review of the literature relevant to resource supply and sustainable development, fast and slow pyrolysis technology, and markets for fast pyrolysis products. This chapter is sub-divided into four main parts; biomass resource modelling, thermo-chemical conversion models, literature review related to market potential for fast pyrolysis products, previous markets for various slow pyrolysis products and chapter conclusions.

The models were described and discussed, and according to criteria it was determined whether the models were useful to data analysis, modelling approach and research methodology. The criteria used to assess the suitability of a model to this research were:

- C1. Link to economic theory and national policy indicators
- C2. Spatial considerations
- C3. Dynamic features
- C4. Link to other sectors and land use issues
- C5. Model and data availability and model adjustments needed.

The criteria are discussed in greater detail under each model considered relevant to this research. If a criterion is not discussed, that model does not present a basis for further consideration. A review of literature in the context of; wood-based biomass resources and prior or existing uses thereof, and prior and exiting uses of slow and fast pyrolysis technology in Namibia and South Africa is provided under chapter sub-divisions. Literature review on markets for fast and slow pyrolysis products is discussed in section 4.5.

4.1 REVIEW OF LITERATURE ON BIOMASS RESOURCES MODELLING

The objective of this section is to review literature and analyse models on biomass resources, and in particular wood-based biomass resources. Many biomass resources models were found, but after preliminary assessment only two models were considered to be of particular interest to this research, namely:

- The Policy Analysis System (POLYSYS) [180];
- A conceptual model of vegetation dynamics in semiarid highland savannah of Namibia, with particular reference to bush thickening by *Acacia mellifera, sub-species detines* [301].

4.1.1 Review of literature on wood-based biomass resources production in Namibia

Of Namibia's land surface area, some 60% are desert or semi-arid areas which allows no or only limited levels of agricultural production, both livestock (domesticated and wild animals) and crop production.

It is reported that due to uncontrolled overgrazing, agricultural malpractice, long term severe droughts over decades and cyclical rainfall patterns, the grass component for animal food which makes up approximately 20% [88, 89] of the biomass produced, has been overexploited. The latter events led to increased bush encroachment and loss of biodiversity, as one of the consequences [98].

The ultimate concern over bush encroachment for Namibian authorities is loss of environmental and socio-economic sustainability [81] of especially the livestock production sub-sector within the agricultural sector. As agriculture remains one of the economic pillars of the Namibian society and economy, the National Development Plan 4 (NDP4) [90], covering the period 2012/13 to 2016/17, *inter alia*, promotes strategies and activities that "*increase the land's carrying capacity for livestock*". The latter is to be accomplished by

> "*Debushing, as a strategy for increasing grazing land in order to improve productivity and create employment in the sector (agriculture), will be encouraged and supported. These activities will be pursued and scaled up across the country, with a specific focus on labour-intensive debushing*."

Based on the aforementioned stance of Namibian authorities, this research accepted that bush encroachment must be reduced substantially. Support for debushing and land rehabilitation activities following bush encroachment can be expected from the Government of Namibia [81, 90]. However, the level of support (political and monetary) is not explicitly mentioned, but is expected to be provided through annual national budgetary allocations and technical support (also from international development and/or finance institutions) towards debushing initiatives.

Literature on the exact causes of bush encroachment could not be found. A national inventory system for bush encroachment in Namibia is not available. Data for certain regions is available as illustrated in Figure 5-1 and as explained by de Klerk [265]. Research to date has mainly concentrated on specific areas or a specific species declared as encroacher-bush [282, 82, 265, 88, 102, 262, 91, 92]. A comprehensive national database or model establishing how to assess the inventory or growth patterns of encroacher bush was not found. As bush encroachment is said to negatively impact on agricultural output, that is mainly livestock production [265, 88, 89, 97, 102, 116], a relationship between bush encroachment and livestock production was endeavoured to be sought and will be discussed further in section 6.1.

In an effort to investigate causes of bush encroachment and possibly an indication on bush inventory and growth pattern, some 100 respective farmers in general, and livestock producers in particular across Namibia were interviewed. The focus of the questionnaire was on how they are noting the effects of bush encroachment and how they perceive it to be relating to livestock production output. Farmers were also questioned about other factors that contribute to an increase in bush encroachment. The interviews were conducted in the period 2008 to 2011. Online questionnaires were distributed via the Namibia Agricultural Union, and returned electronically. Most interviews had to be conducted personally and/or telephonically as only some 40% of the questionnaires were returned electronically. The summarised responses and explanations are provided in Table 4-1.

Table 4-1 Summary of responses received from farmers on bush encroachment; its causes, effect and growth patterns

Summarised Responses to:	The effect of bush encroachment on livestock production	The farmers' arguments why bush is encroaching farmland predominantly used for livestock production, and how they control bush encroachment on farms
Factors contributing to bush encroachment & the predominant effect	In general, for all bush encroachment affected areas, carrying capacity of the farmland reduced between 20 to 43 percent.	Preserve a conservative livestock stocking rate.
Causes of bush encroachment & the duration of on-farm bush encroachment	In general, for all affected areas, livestock held had to be reduced as the land available for grazing decreased.	It is clearly observable that where cattle graze, and overgrazing was prevented, the quality of grazing is substantially improved since the cow dung is easily processed by dung beetles and dissipated by the rain. Biodiversity changes after 50 years if no prevention is maintained; large game species start to dwindle; but if bush encroachment is contained, game diversity seems to return rather quickly, even birds seem to return in masses.
What the effect of size & density of bush encroachment is on the farming system	In general, for all affected areas, less perennial grasses are available as it is noticed that grass does not settle under bush; it is noticed that the quality of grass is maintained though. At the same time, for all affected	Support of any actions to selective poisoning of encroacher bush is welcomed, as some farms are relatively small and it can only be positive to increase the grazing capacity and the quantity and quality of grasses.

Summarised Responses to:	The effect of bush encroachment on livestock production	The farmers' arguments why bush is encroaching farmland predominantly used for livestock production, and how they control bush encroachment on farms
	areas, the quantity of seasonal or annual grass species was noticed to have increased due to bush encroachment.	
How the farmer perceives bush encroachment overall, in national context	The reduction of livestock only affected large livestock units; no reduction in small livestock units is/was necessary; equally, no reduction in game numbers was observed.	Keep farm management as natural as possible: fire, browsers, no over grazing.
How the farmer perceives bush encroachment overall, at on-farm level	In general, it is noticed that bush encroachment forms 'islands' of very high bush density. These 'islands' are made of normally one specific encroacher specie. And, these 'islands' are noticed to be shelters for game and small livestock. However, too many of these islands would rather relate to the effect as described in responses in 1 to 3.	It is important that some islands of *Acacia mellifera spp detines* are maintained for the game and also on top of the hills to break the wind.
What the effect of extra-ordinary events and weather/climate patterns is on bush growth	General bush dieback occurred during consecutive drought periods; and/or prolonged frost periods during winters. Bush encroachment is noticed to explode in years of high to very high rainfall, following consecutive years of drought; however, in the years of high to very high rainfall; grass production in general is noticed to be good in years of higher than 'normal' rainfall. Mean annual day and night temperatures are observed to influence bush encroachment patterns.	The overall high rainfall over the last 12 years contributed to bush encroachment. It is very visible that during the peak rainfall years of 2000, 2006, and between 2009 and 2011 most germination took place, even if farms were under stocked since around 1990 up to date. Increased sprouting/ coppicing is noticed after the good rainy season 2010/11. The higher grass production seems to help to contain further bush encroachment by preventing sprouting of bush to some extent. Prolonged frost in winter months kills small bushes which sprouted or coppiced in good rainy seasons. Lack of frost or 'warm winters' was noticed to invigorate bush growth.
Whether a certain farm management system affected bush growth patterns, and how	Poor land management practices are noticed to have had an effect on bush 'explosion'; especially the switch from dairy to meat livestock holding, and from small to large livestock have been noticed to have been conducive to bush encroachment.	It is very visible that bush encroachment is predominantly on farms where sheep have been kept in the period 1946 to +/-1984. Fencing in/off with 7 wires, are therefore not suitable for keeping of goats which are browsers. Furthermore, dairy farmers kept trekking ways for cows to be milked. These trek ways today are highly bush encroached.

Summarised Responses to:	The effect of bush encroachment on livestock production	The farmers' arguments why bush is encroaching farmland predominantly used for livestock production, and how they control bush encroachment on farms
	Bush encroachment, when contained by various methods is noticed to have a positive effect on perennial grass quantity, improved carrying capacity of the farmland and increased ability to hold greater numbers of large livestock and game.	Don't hold small stock together with large stock; goats tend to browse extensively and thereby spread seeds of bush. Sheep overgraze the rangeland thereby limiting carrying capacity further. Bush encroachment has no enemies; dedicated interventions are needed to manage it. However, bush encroachment management or treatment is very cost intensive and therefore many farmers don't do it. Bush encroachment containment / prevention is very costly, time consuming and often skills of workers are lacking. Since 1990, MAWF extension officers don't provided adequate advice any longer. This advice is now obtained from arboricide sales' personnel or from other farmers. Aftercare is recommended as the best means to contain bush encroachment. Where bush encroachment was managed 10 years ago, bush is back today! One-off treatments are not sufficient either, and if no after care is done at all, bush thickening may be worse afterwards, which is specifically experienced with *Dichrostachus cinerea*. Due to removal or poor maintenance on fences, it is difficult to control game movement resulting in the destruction of the more palatable grasses, with an increase in weeds and poisonous plants. Thick bush (bush encroachment) has always been a "problem" in Namibia. Before there was enough land to buy or lease. These days not any longer. Therefore debushing must be done to win/obtain more grazing land. Aerial spraying is not an option as it would destroy tree species where birds normally nest, especially for sociable weaver birds. Lack of or even access to proper documented research seems to hamper progress in the field.
Whether there are other effects of bush encroachments that cannot be observed (possibly requiring in-depth research)	Respondents, in general, have not highlighted that bush encroachment had a specific effect on groundwater levels.	

The outcome of the interviews was used in Chapter 6 to establish a bush re-growth rate as well as annualised, disaggregated bush inventory data for Namibia. This was considered necessary as bush encroachment data (section 5.1.1) was found to be discontinuous and based on total national area being bush encroached.

4.1.2 Review of existing uses of wood from bush resources in Namibia

In the context of the bush encroachment, various studies were carried out over the past years to make use of the "debushed" material [93]. Until the launch of the National Rangeland Policy in September 2012 [81], the main area of interest concentrated among the commercial (freehold) farmland areas. Projects to combat the spread of bush encroachment in the commercial farming areas [94, 95] have ranged from large scale herbicide application [92] to controlled bush fires [96], and recently to more sustainable bush utilisation projects [97, 98]. The bush utilisation projects include firewood production, chipboard and composite wood-chipboard production, wood briquettes, charcoal and charcoal briquettes production [99, 100, 101], bioenergy production systems [102, 103] and 'complete wood-based' industry systems [104, 105, 282]. Commercial use of wood biomass in communal farming areas only started after Namibia's independence in 1990 [106]. There has been considerable interest in the utilisation of invader bush in the last 5 years. Not only to recover the costs of bush harvesting/thinning, but also to establish potentially viable Small or Medium Enterprises (SMEs) in rural and communal land areas of Namibia, and to diversify the economic opportunities on offer in Namibia.

Apart from firewood and charcoal production which is regulated, all other initiatives are cottage industries serving the domestic market. The existing total production of firewood and charcoal together is less than 1Mt per year [58, 107, 116]. Firewood is mainly exported to South Africa; charcoal is exported to Europe (UK) mainly and South Africa. The total annual Namibian charcoal production varies from 25–40kt and the statistics depend strongly on who provides the information. Of this annual production, about 60% is directly exported under the Forest Stewardship Council (FSC) label to Europe into the barbeque market, 30% is exported in bulk under the FSC label to South Africa, and only 10% is consumed within Namibia. Charcoal production and trade statistics are not captured and maintained regularly, and the National Accounts of Namibia do not register individual commodity imports or exports. Charcoal production and export data was obtained from charcoal producers [108]. The charcoal production potential in Namibia is estimated to be very high and could be as high as that of South Africa, but limited by the technologically unsophisticated conversion methods (section 4.5.1.1; Table 4-6). Technological improvement could increase the yields and quality of the charcoal without increasing the amount of feedstock required.

Many domestic and foreign investors have shown an interest in using Namibia's biomass potential for charcoal production and power generation [116]. To date and even though a number of extensive studies have been carried out over the past 30 years, there is still no coherent summary of the full socio-economic and ecological potential of Namibia's sustainable bush biomass either as an energy carrier or a source of other renewable products [109, 116]. Commercial uses of wood from encroachment bush in Namibia for composite building materials were piloted, but failed [116]. The reasons for failure cited were lack of project management skills and insufficient funding. Trials to use invader bush for power generation on a national scale basis were carried out between 2006 and 2010 [282, 102]. However, no commercial operation has been started up to date. Nampower, Namibia's bulk electricity provider completed a prefeasibility study in 2013 [110, 111], to investigate the viability of using wood from encroachment bush in mainly combustion systems for on-grid power production systems. Nampower's aim with the pre-feasibility study was to present the results to possible independent power producers for their use as a decision making tool to possibly set up power production systems. Nampower would then 'guarantee' power procurement from them.

Between 1970 and approximately 1995, multiple Namibian government institutions, mainly hospitals and schools with boarding facilities, were supplied with bulk firewood for heating of water. The Namibian government exchanged the wood-fired boilers with electrical heating or bunker oil-fired systems [116]. An initiative to use wood from bush encroachment as a source of energy for the production of cement was initiated in 2011 [112]. The sourcing of the wood is concentrated in areas within 75-100km radius of the cement factory due to prohibitive transport costs in relation to the resource's value beyond the latter radius.

The 'real' domestic consumption, other than for mentioned industrial purposes of firewood and charcoal is not known. Only recreational firewood and charcoal trade through formal channels is accounted for. It is therefore assumed that 1.5kg of firewood per capita per annum is used in Namibia, or a 41.79 TJ in total [113]. The assumption is based on consumption patterns as computed under South African conditions (section 4.1.4) and the most recent National Household Income and Expenditure Survey 2009/2010 (NHIES) [114]. Firewood in Namibia is used for recreational purposes (urban formal settlements) and cooking and space heating (urban informal settlements and rural areas). Charcoal for domestic recreational purposes is accounted for under firewood for recreational purposes. The domestic retail value of recreational firewood is over NAD2.2k/t; the value of charcoal over NAD10k/t.

Authorities have recognised the opportunities and constraints in developing sustainable industries concerning the use of wood biomass in Namibia. Opportunities lie in improved agricultural potential, improved energy security coupled with improved air quality through the reduction of burning fossil fuels, new economic and technological opportunities, and scientific innovation in technology and market mechanisms introduced through the Kyoto Protocol, and more recently the Copenhagen Accord [115].

The above mentioned positive developments seem to be constrained by the ability to develop a new biomass resource based industry in Namibia itself [116]; agricultural potential in Namibia is limited by erratic climatic conditions and depends on sustainable use of scarce water resources. Potential production areas are remote from economic hubs or even urban areas, requiring the resolve of meaningful decentralisation in Namibia. Access to broad know-how and technology base and innovative funding modalities confine projects to a limited size or mere one offs [39].

Since there is great emphasis by authorities on the utilisation of bush for income generation, job creation and poverty alleviation [90], their focus remains on investigating socio-ecologically sound management practices. These developments have added a new dimension to the conventional mix of bush encroachment management strategies, which previously, with the exception of firewood and charcoal production to augment farming income, have not considered biomass as an asset [109, 116].

In the Namibian case, the question therefore to be answered by this research is – can a benchmark be established to use bush for bioenergy in a sustainable manner? Subsequently the following needs to be established as well: What are the parameters that need to be established to build such benchmark? Is the Namibian socio-economic and techno-economic environment ‘right’ to embrace a modern bioenergy system? Sections 4.2.1 and 4.2.2 provide an analysis on how to establish the wood-based biomass model, which would be linked to the bioenergy roadmap as discussed in section 10.2 (recommendations).

4.1.3 Review of literature on wood-based biomass production and uses in South Africa

South Africa is rich in various types of land cover which could potentially be utilised to produce bioenergy. Substantial work has taken place in classifying and quantifying the vegetation types of South Africa. Some of this pioneering work was started in the 1940s [117, 118] and continues to receive attention from South African authorities and international organisations [121, 122]. Data is readily available in different formats (e.g. in spreadsheets or as meta data), but may need some patience to gather as it is spread over various literature. Data for South African wood-based biomass is discussed in Chapter 5.

South African authorities [7] consider the following biomass resources for energy production as commercially exploitable, though exploitation thereof is considered to remain less optimal for energy production, especially electricity production [119]:

- Agricultural waste – bagasse, wood chips and cuttings from forestry operations, corn and wheat husks and stalks, manure
- Energy crops, for
    - bio-ethanol from maize, corn, sugar cane
    - bio-diesel from soya beans, jatropha, palm oil, algae
    - others from switch grass, triticale.

The focus remained on the various types of wood-based biomass as established in section 3.1.1. Natural Grassland biomass (grassland as classified by the vegetation Table 4-2), and residues from agricultural operations (from crops and horticulture) were considered by this research initially. The sustainable quantity available from natural grassland, based on its mean annual increment is not quantified and no indicative research data is available so far [150]. Data on the specific quantities that could be available for thermo-chemical conversion, in particular fast pyrolysis, from residues or waste of agricultural operations concerning cash crops and horticulture, could not be isolated from the data presented in official statistics. The official statistics available present data on total production (in tonnes), and its value (in South African Rand), but not yield or waste/residues remaining from amount of production sold or used elsewhere. It is acknowledged by this research that energy crops and residues/waste from, e.g., the food and agricultural sector is a feasible feedstock for fast pyrolysis conversion. Nonetheless, sourcing and analysing data on potential energy crops and utilising wastes from the food and agriculture is beyond the scope of this research. The wood-based biomass resources having potential for fast pyrolysis conversion to energy pertain to the following vegetation types in South Africa (Chapter 5):

- Forest biomass (wood-based plant material from the various forest types);
- Residues and waste from forest operations and wood primary and secondary processing; and
- Biomass derived from eradication of invading alien plants under the “Working for Water” programme (wood based and where feasible, other plants) and bush-encroached areas.

To establish the commercial exploitability of the wood-based biomass resources, the estimated total area under woody vegetation cover is of importance, including thickets, or areas where invasion from certain plant species has occurred. The total potential of wood-based biomass resource available for fast pyrolysis conversion is established as the mean mass and energetic potential on an annual basis in the presence of competing markets as indicated in section 6.3.

In computing the energy potential of wood-based biomass, it was important to know how accessible these areas are for possible fast pyrolysis conversion of wood-based biomass to energy, whether for commercial utilisation or for community utilisation. The various land cover classifications available to date were published by the FAO ‘Forest Resources Assessment – South Africa Country Reports of 2005 and 2010 [121, 122]. Land cover information, consistent with the FAO’s categories and definitions are based on the work done by Fairbanks [120] which was subsequently published in 2000 [122]. The data published by the FAO [121], based on land cover in 2005, was only published in 2010. FAO [121] states that a complete forest and land cover inventory is on-going in South Africa and that field inventory research and remote sensing survey/mapping would be completed in 2012. The currently available data of land cover as published by authorities and FAO, is used in modelling bioenergy production from wood-based biomass; the data was found adequate for estimations of future trends.

Table 4-2 Land cover description of South Africa as reported in 2010 (rounded to the nearest ha) [121, 122, 123]

Land Cover Type	Calibrated Area (ha) in 1995	Calibrated Area (ha) in 2000
Forest	402,016	515,718
Woodlands (in 1995 classified as forest and woodland)	7,022,481	9,219,818
Forest plantations	1,793,151	1,722,947
Thicket, bush land, bush clumps, high fynbos (in 1995 classified as thicket and bush land)	21,443,701	21,957,271
Shrub land and low fynbos	41,581,091	42,005,260
Cultivated land	14,776,993	12,766,493
Degraded land	5,656,750	1,730,934
Degraded forest and woodland (new in 2000)		1,609,933
Degraded thicket, bush land, bush clumps, high fynbos (new in 2000)		1,164,275
Urban or built-up land: residential, small holdings, woodland	40,528	30,462
Urban or built-up land: other	1,360,635	1,830,478
Dongas and sheet erosion scars	186,814	640,324
Barren rock	260,780	119,902
Herb land	243,387	213,984
Improved grassland	128,409	294,255
Wetlands	582,673	1,300,241
Water bodies	461,701	599,332
Mines and quarries (new in 2000)		202,156
Unimproved grassland (new in 2000)		24,030,993
TOTAL	122,104,002	121,954,777

The forestry sector is divided into three sub-sectors, depending on the type of forest resource being dealt with, i.e. commercial, community and conservation forestry. These sub-sectors by-and-large directly correspond to commercial plantations (section 4.1.3.2); woodlands or savannah (section 4.1.4); and natural or indigenous forests (section 4.1.3.1). Natural, indigenous or conservation forests are protected by law and therefore not considered as possible feedstock for fast pyrolysis conversion. However, large quantities of invasive alien wooded plant species that need to be eradicated by the 'Working for Water' (WfW) programme grow in indigenous or conservation forests (section 4.1.5). Wood-based biomass from commercial plantations is limited due to legislative measures that restrict the planting of these mostly (and potentially invasive) alien tree species in South Africa. Thus, land allocated to commercial plantations is unlikely to be increased, and the land size for the period 1979 to 2003 remained mostly unchanged.

This section provides as much information as possible on the current uses of the various types of forest biomass available in South Africa. There may, however, be data discrepancy as sources of information did not provide for data consistency; or data was based on estimation. Whichever the case may be, it was indicated as such.

4.1.3.1 Natural Forest Biomass Resources

The total mapped area of natural forest (also called indigenous forest) in South Africa covers less than 1Mha and cannot be used for industrial purposes by law [134, 148]. The natural or indigenous forest areas of South Africa can mainly be found in the Western and Eastern Cape. Indigenous or natural forests are utilised for recreational purposes and are protected in terms of various legislation, notably:

- Conservation of Agricultural Resources Act, and as amended in 2001 and its amended regulations [60, 170];
- the National Forest Act [124];
- the National Environmental Management Act [125,] and as amended by the National Environmental Management Amendment Act [126, 127, 128] (Act 8 of 2004) and its environmental impact assessment regulations as implemented on 1 July 2006; and
- the National Environmental Management Biodiversity Act [129].

Natural forests and commercial plantations occur in the same South African provinces [130]. This is mainly due to the climatic conditions required for production of forest types, where rainfall is the key driver of biomass stocks and primary production [150].

Land ownership of natural forests in South Africa is not known directly, but can be inferred, to some extent, by the level of protection. It is assumed that forest patches that do not have some form of regulatory protection have either communal or private ownership. Almost half of all natural forests in South Africa are found on private property or land under communal tenure [134]. Ownership and status of protection of forested land is important as this determines who may use the resource, other than commercial use, unless infestations by alien tree-plant species have been identified.

Utilisation of biomass from natural forests is not allowed for commercial purposes, these forests play an important socio-economic role, i.e. support in majority to the small, indigenous furniture industry and provides for the supply of fuelwood (charcoal and firewood) to local, mostly rural, communities living near these forests.

4.1.3.2 Wood-based biomass resources available from commercial forest plantations

Commercial plantation forestry in South Africa started in the 19th century [131] and encompasses the large planted forests - established to supply raw materials to satisfy mining, construction, and industrial markets as well as resource supply to pulp mills, sawmills and other factories. The total commercial plantation area is limited politically to between 1.3 and 1.5Mha [132]. The total area of plantation forest is decreasing over time due to continuous land restitution (the political term used in South Africa for compensation of land unlawfully expropriated before 1994); non-transferability of plantation licenses and the accompanying cumbersome licensing procedures, and degradation of plantations due to fire [120, 136,]. Table 4-2 indicates that more land is under commercial forest plantations than data obtained from Forestry South Africa [132, 133]. From explanations provided by the FAO [121] and Forestry South Africa [132], the discrepancy can be attributed to integrated woodlots, windbreaks within forest plantations and abandoned land. To model bioenergy potential in South Africa, the land cover data provided by Forestry South Africa is used; commercial forest production is based on 1.3-1.5Mha, and not on approximately 2Mha.

South Africa's commercial forestry sector is well documented with data on various aspects of this sector captured since 1979. Available statistics lag behind by two to three years, depending on the data source, and are captured as fiscal years [133] spanning from March of a year to February of the next year. The information is readily available from Forestry South Africa [132] and the Department of Agriculture, Forestry and Fisheries, South Africa [134].

The majority of the timber plantations are in Mpumulanga (largest area) and Kwazulu-Natal (2nd largest area) province. Although Mpumulanga has the largest plantation area, Kwazulu-Natal produces the most wood. Other plantation areas are found in the Eastern Cape (3rd largest area); Limpopo (4th largest area); Western Cape (5th largest area) and a small amount in Gauteng Province. Figure 4-1 provides an overview of the total production area of commercial forestry for the production cycle 1979/80 to 2007/08. Of the production area, around 80% of the area is said to be certified under the Forest Stewardship Council (FSC) as sustainable forest production areas [134, 135]. The average, aggregate timber production is 15t/ha [136, 137].

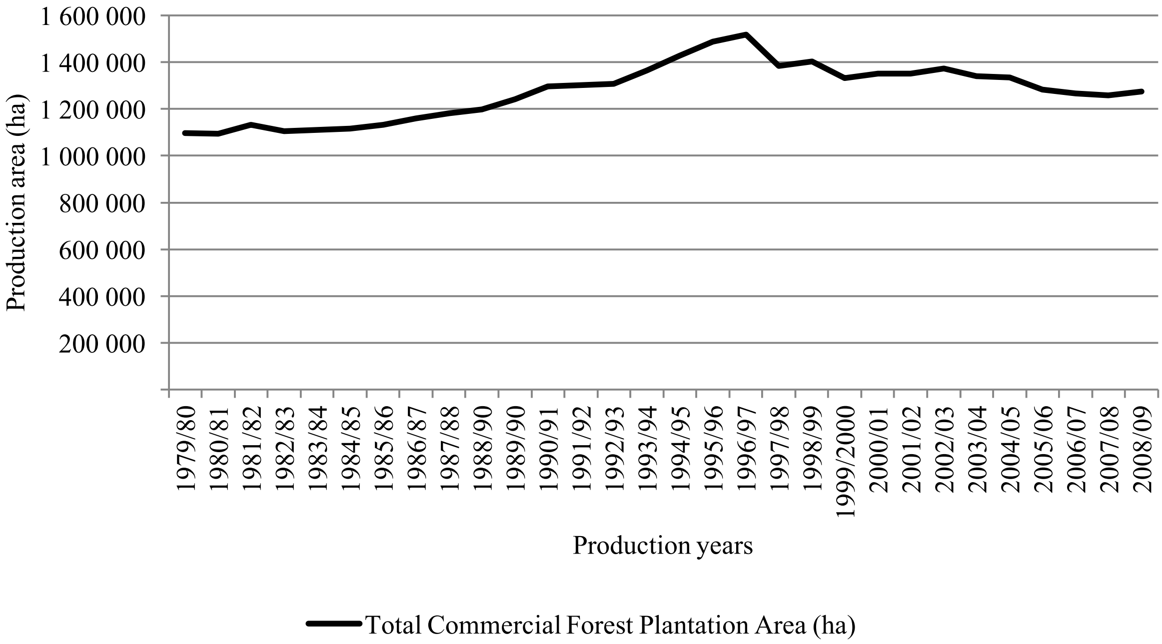

Figure 4-1 Total commercial forestry area (ha) developments for the production years from 1979/80 to 2007/08

The commercial forest produce is subsequently delivered to the saw milling industry, paper, pole and charcoal production (section 6.2.2.). Of interest to this research is the amount of wood chips or other wood-based residues that could be used for bioenergy production via fast pyrolysis; the total amount of production over the past 30 years is visualised in Figure 4-2.

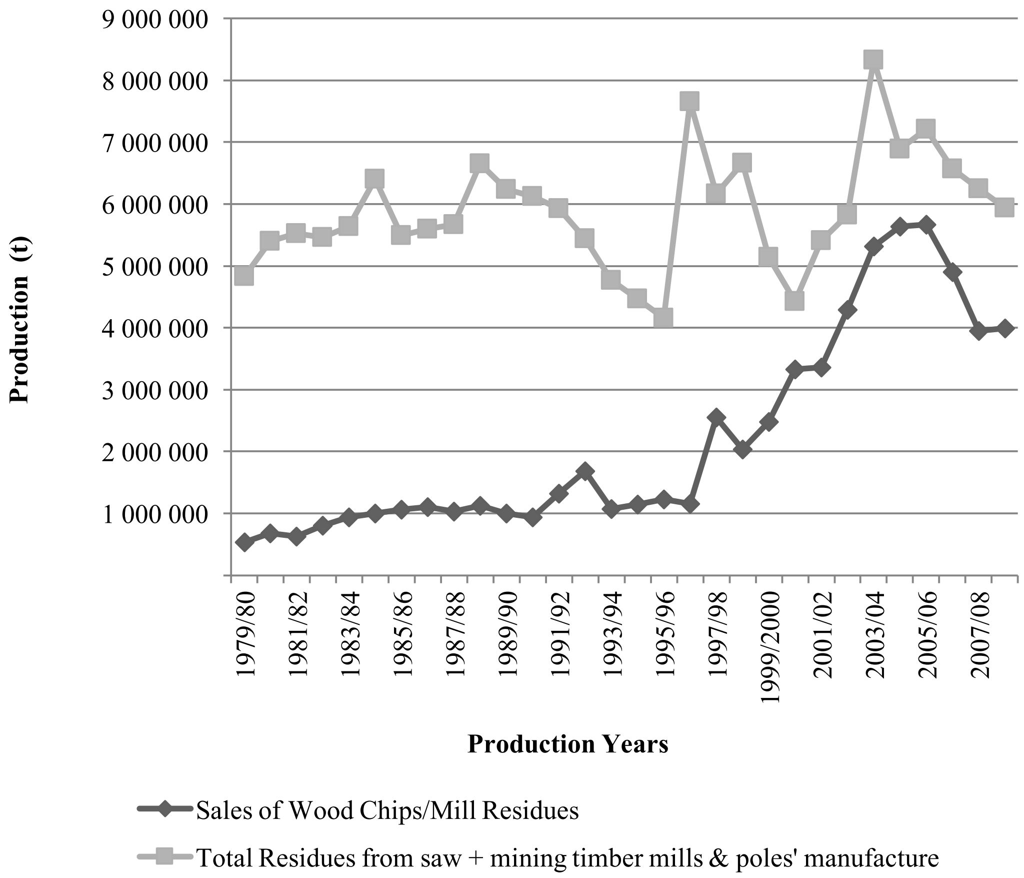

Figure 4-2 Total weight (t) of wood chips production and wood-based residues in South Africa for the production years from 1979/80 to 2007/08

The species grown for commercial round wood production are softwood species, i.e. various *Pine* species which are highly adapted to the South African climate, *Eucalyptus grandis* and few other adapted *Eucalyptus* species, *Acacia mearnsii* (Black Wattle), Poplar (became a negligible source for timber as from the mid-1990s) and other adapted hardwood alien species. These species were selected for their suitability as saw logs, mining timber, pulpwood, matchwood, poles, wood chips mainly for export and fencing materials. Thinning and pruning of these are also used as sources for domestic fuelwood and charcoal production (via slow pyrolysis).

Figure 4-3 provides an overview of round wood sales from plantations vs. the intake of round wood by primary processors from production years 1979/80 to 2006/07 [138]. The amount that could be used for bioenergy production is modelled and discussed under section 6.2.2.

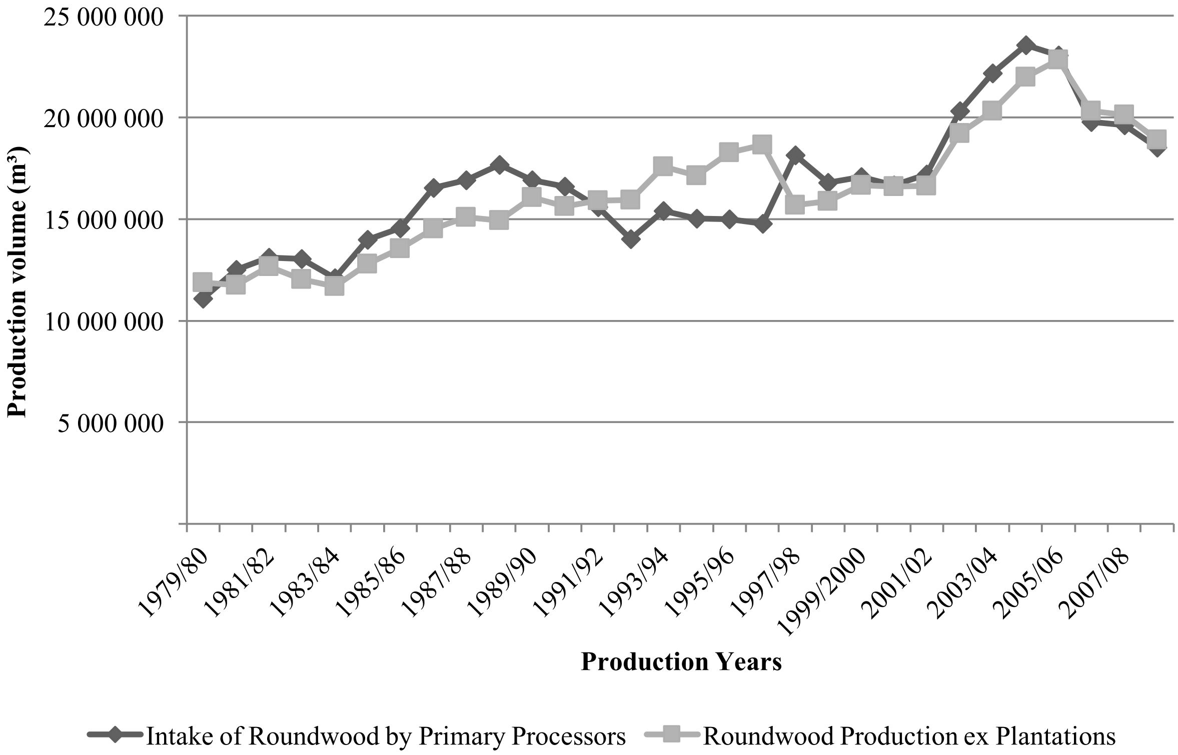

Figure 4-3 Annual round wood production at plantations and corresponding intake of round wood by primary processors from 1979/80 to 2008/09 [138, 139, 140, 141]

A complete assessment of round wood sales (based either on volume or metric tonnes basis) since 1979/80 is carried out in terms of the total South African commercial biomass resources by Forestry South Africa on an annual basis and are published each August. The data has been consistently produced and accounts for the total commercial forest plantation area; new afforestation area; area converted to other uses, including for agricultural production; types of forest (per area) and their uses; primary conversion volumes; sales of primary product (volume and/or weight) and value (South African Rand and US Dollar); and the contribution of wood-based forestry production to the overall economy. The data is also used for monitoring and reporting purposes to the national regulator, that is, the Department of Agriculture, Forestry and Fisheries.

It is assumed that the future potential of converting wood biomass from this source to produce energy will not compete with existing uses. In data sets assessed, the direct main source of plant biomass from forest plantation is already used for slow pyrolysis processes and is labelled 'firewood/charcoal (wet tonnes)'; a further data set is labelled 'intake of round wood by primary processors (wet tonnes) for charcoal plants'. It is assumed that wood resources labelled firewood, charcoal and charcoal plants are not available as resources for fast pyrolysis as discussed in this research. An overview of the total biomass resource thus assigned for conversion in firewood and charcoal production systems is provided in Figure 4-4. The charcoal plant intake regularly exceeds round wood production as charcoal producers do not only source their feedstock from commercial forestry plantations, but also from imports, e.g. Namibia; waste and residues from primary wood processing industries, such as saw milling; and the 'Working for Water' public programme (section 4.1.5).

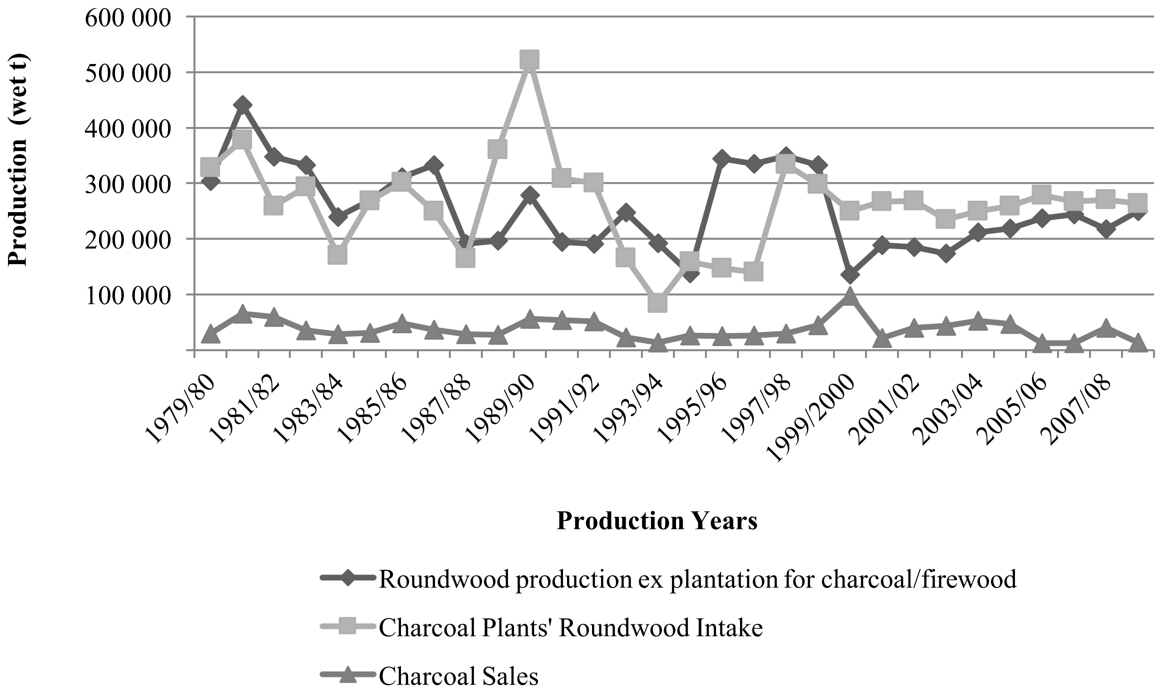

Figure 4-4 Round wood production for firewood/charcoal and corresponding round wood intake for charcoal production from 1979/80 to 2008/09 [138]

All other timber uses have a round wood intake which is different from the yielded primary product achieved. This suggests that sufficient 'waste' is produced for possible secondary conversion to energy from such biomass resources. The Forestry South Africa data set indicates that there is indeed biomass available from primary processing plants and is labelled under 'sales of timber from primary processors (tonnes) – wood chips/mill residues':

- One part of this 'waste' is sold to the pulp and chipboard manufacturing industry domestically as an additional source of fibre – and if the pulping industry does not use the material as fibre, the primary conversion industry uses the waste as a source of energy to generate heat or power.
- A second part is exported as 'debarked wood chips' to mainly Japan.

- A third part is used by the charcoal industry; the majority of the charcoal industry maintains that this material is not suitable for charcoal production *per se* but only as a source of heat to get the kiln process started. The latter was established by interviewing South African charcoal producers in the provinces of Eastern Cape, Gauteng, KwaZulu-Natal, Limpopo, Mpumulanga, North-West and Western Cape between 2006 and 2008. Residues of considerable size are sold as firewood, and are accounted for as shown in Figure 4-4.
- A fourth part is collected by nurseries to make mulch and potting soil, mainly from residues containing high amounts of bark.
- A final part is considered as waste material and consists mostly of bark material (too much to generate heat or power efficiently; or to make mulch) and degraded chip material. The exact quantities of this final 'waste' material available for further processing are not known as the data source does not provide disaggregated figures for the final destination of the wood chips/residues.

What however becomes clear from the data set is that the resultant amount of wood chips/residues actually sold to third parties has grown ten-fold between the production years 1979/80 and 2007/08, even considering the major decline in sales between 2005/06 and 2006/07 (Figure 4-5). It is assumed that the difference is the additional resource available for bioenergy. How much of the resource is indeed available for bioenergy is modelled and discussed in section 6.2.2.

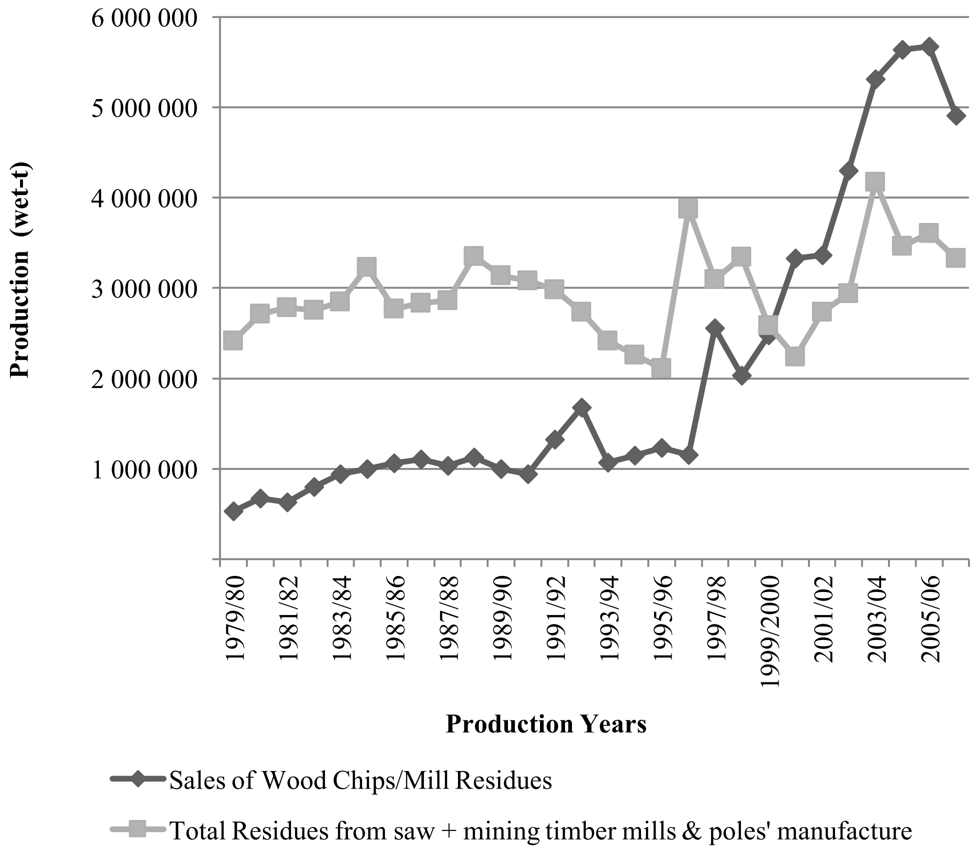

Figure 4-5 Total amount of residues from saw & veneer mills, mining timber mills and pole manufacturing in relation to sales of Wood Chips and Residues from production years 1979/80 to 2008/09 [138].

In addition, not all biomass from timber production is suitable as round wood for commercial use. A considerable amount of biomass accumulates during the growing and harvesting of round wood. This potential source of biomass for conversion to either energy includes:

- Wood from pruning and thinning young stands;
- Waste resulting from the first silvicultural thinning (coppices, unsuitable round wood);
- Logging residues (incl. stems, undergrowth, tops or crowns, branches) from the final cutting areas; and
- Low quality trees with no commercial value.

This residue or foliage is normally expressed as a percentage of the round wood (trunk) mass. A report done for the Department of Minerals and Energy, South Africa [142], suggests that this figure is 21% for softwood and 16% for hardwood resulting in an average of over 3Mt of forest biomass waste annually between 1996/97 and 2006/07. After consultations with the industry, forest waste as percentage of round wood mass is estimated at 10% for softwood and 5% for hardwood species [135, 143, 144]. After further analysis of data availed by Forestry South Africa, it was found that on average the truly 'utilisable' forest residue available for conversion to bioenergy could be around 20% (wet basis) as a ratio of round wood production per annum, for both softwood and hardwood together. The basis of calculation is a comparison of total production of round wood, i.e. by area and by average annual yields achieved with the actual inputs used by the respective wood-based industries and output of final products.

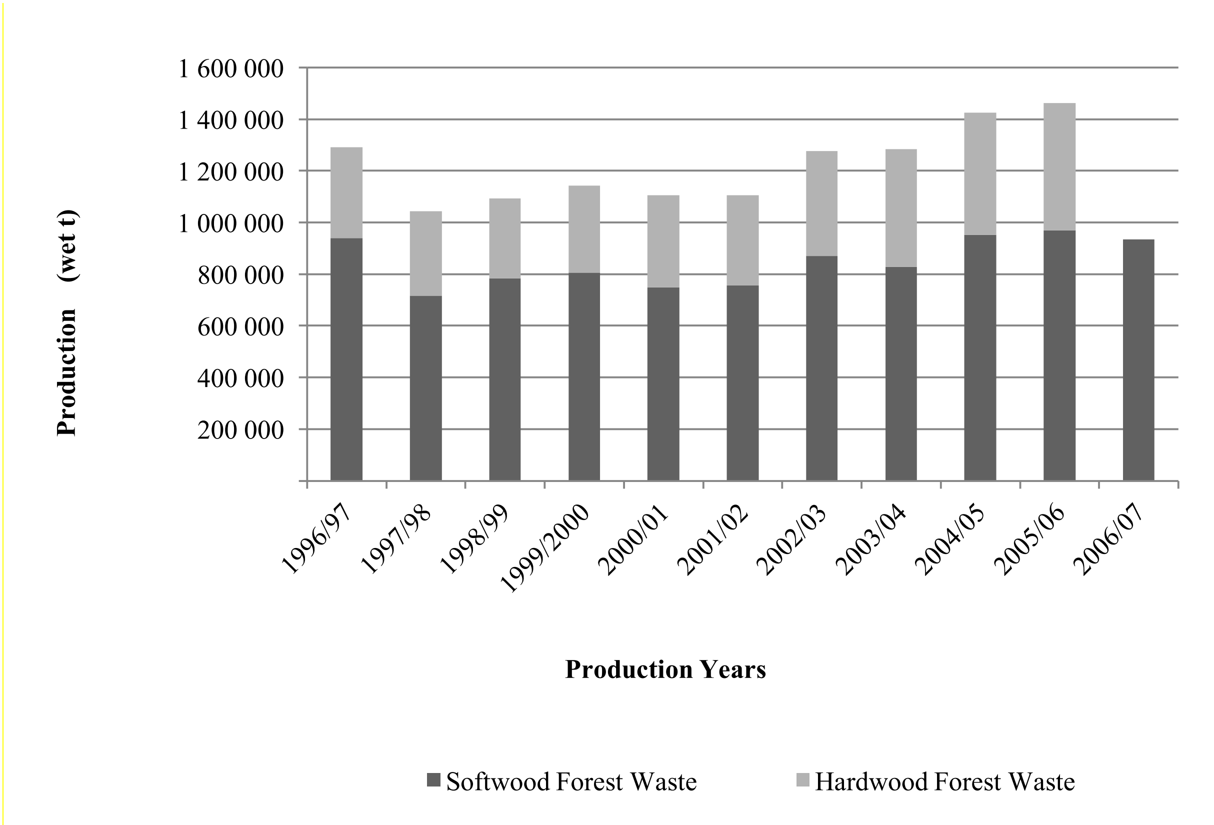

Figure 4-6 Forest waste in commercial plantations after round wood extraction [138]

The forest waste typically consists of foliage, tree tops, smaller coppice sprouts, twigs and bark and makes up half of the total forest waste (i.e. some 10%) as a ratio of round wood production per annum, for both softwood and hardwood. Industry [135, 143, 144] is of the view that the forest waste can serve as a source for additional fuelwood, either for domestic or commercial use. However, for forest land certified under the Forest Stewardship Council (FSC) label, and according to the opinion of ecologists and foresters, forest waste should not be burnt or removed. Forest waste should not be seen as a commercially exploitable biomass resource as it may turn commercial forest operations unsustainable in South Africa; mainly due to unwarranted additional silvicultural costs [145, 146]. The latter resource is therefore assumed as not available for bioenergy.

The other half of the forest waste, i.e. half of the 20% mentioned afore, is available for conversion to bioenergy. The total utilisable proportion of plantation forest residue makes up some 10% of roundwood (trunk) mass, for both softwood and hardwood. The forest residue typically consists of roundwood damaged by logging operations, cut young and/or damaged trees with no commercial value and larger coppice sprouts. Extraction of this wood-based biomass resource is costly due to logistical difficulties [142] as well as geographic distribution across South Africa; and was thus not considered.

There is seemingly an additional biomass resource available from the pulp and paper mill, i.e. bark [142]. The bark component (9% from softwood pulpwood intake; 0.5% from hardwood pulpwood) has been assessed as part of residues available from saw mills, pulp and paper mills and mining timber mills. On average, for the past 10 years, some 320kt of bark waste was produced by pulp and paper mills [147, 142]. The energy requirements to generate power and steam in the pulp and paper industry are not exactly known [142, 28, 147], but are very intensive [24] and estimated at 8% as a ratio of total energy demand of the South African industry sector. It is assumed that most of the bark produced by the pulp and paper industry is needed in-house with little scope for utilisation outside the pulping industry. This resource in South Africa was therefore not considered for fast pyrolysis.

4.1.4 Woodlands and Bush Encroachment in South Africa

The current status of this resource is not well documented and the roles of different service providers in the public and private sectors remain poorly understood [306]. Woodlands are considered to constitute a forest resource of major socio-economic importance in South Africa. It is the most accessible forest and energy resource for poor communities and possibly for other uses, pending further research [306].

Woodlands collectively cover an area of between 29 and 46Mha depending on the woodland classification and/or ownership (Table 4-2, Table 4-3) adopted and various types of woodland vegetation [148, 149, 150]. Woodlands in South Africa consist of wood-based plants and succulents. For this research woodlands classified as predominantly consisting of bush and trees were considered. The area under the latter type of vegetation made up approximately 29Mha in 2010 [121].

Table 4-3 Woodland Types by Ownership in South Africa [148]

Woodland Type	Ownership of Woodland Type (Mha, rounded)			
	Communal	Private	State	TOTAL
High Altitude Acacia	0.3602	8.0027	1.8714	10.2343
Low Altitude Acacia	0.1961	1.4789	0.6760	2.3510
Ghaap Escarpment	0	1.8808	0.2822	2.1631
Kuruman	0	0.6930	0.0597	0.7527
Southern Renosterveld	0	0.0176	0.0004	0.0181
Waterberg	0.0256	1.1094	0.0892	1.2243
Combretum	0.6010	4.7212	2.6071	7.9293
Soutpansberg	0.0059	0.3525	0.0708	0.4292
Spekboom	0.0168	0.6949	0.0903	0.8019
North Succulent Thicket	0.1304	0.3741	0.0168	0.5214
South Succulent Thicket	0.1899	0.3351	0.0276	0.5526
Mopane	0.0066	1.1531	1.1647	2.3244
GRAND TOTAL	1.5326	20.8136	6.9561	29.3023

The Department of Agriculture, Forestry and Fisheries has assessed the ownership of woodlands [134]. Land covered by woodlands is also owned and managed by the state, communities and private people or companies; and may fall under protected or non-protected woodland area. The availability of this resource for bioenergy depends on the ownership. Harvesting of biomass in protected woodland areas is limited to communities living inside or adjacent to these areas, and for residential/domestic use only [148, 151]. Harvesting of biomass resources from state-owned woodlands depends on the willingness of the state to avail such a resource on a commercial basis; the process how such access is to be gained is not pursued further by this research. Access to and harvesting of privately-owned woodlands can be dealt with on a commercial and direct contractual basis between the interested parties.

According to a Baseline Study [148] there are scattered patches of woodlands (including thickets) amounting to approximately 4.7Mha within the remaining parts of South Africa. Woodlands bear potential for diversified utilisation of the wood resource, but extraction and industrial scale conversion of wood into bioenergy would be a challenge as the resource is owned by multiple parties and may not be accessible due to geographic limitations. It is assumed that commercial utilisation of the biomass from woodlands shall mainly be drawn from private, not-protected and actual woodland areas. An overlap in woodland types that are owned by communities or the state and that are protected woodland areas may occur.

In addition, the Working for Water (WfW) Programme, a programme established by the amendment to the Conservation of Agricultural Resources Act (60), has assessed that large woodland areas are invaded by both indigenous and alien plant species with very dense cover, that is a woody plant canopy cover of more than 50% as shown in Figure 4-7. The WfW programme has indicated the need to clear woodlands from encroachment and eradicate the identified alien plant species from the affected areas to, among other objectives, restore biodiversity and free up water resources. Woodlands are a potentially large source of biomass and make up close to 4% of South Africa's land area, or four times possibly the resource available from commercial plantations, subject to biomass yield per hectare achievable. Woodland areas with more than 50% canopy cover (Figure 4-7, shaded grey), and their land classification as expressed in Table 4-2, are of interest to this research. The projected available wood-based biomass for fast pyrolysis from woodlands follows after the description of the current uses of this resource. For the purposes of this research, attention was given to those land areas where bush encroachment occurs, and were treated in a similar manner as bush encroachment treatment in Namibia.

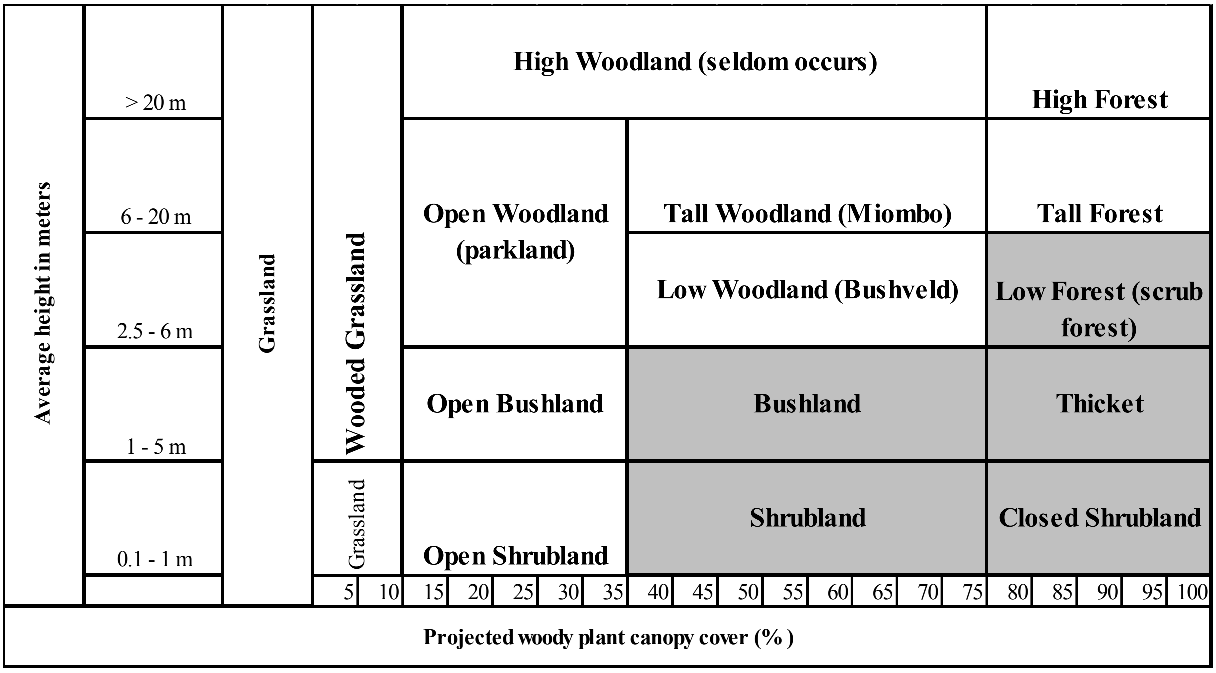

Figure 4-7 Classification of wooded vegetation types, indicating those included in the woodland definition adopted by Department of Agriculture, Forestry and Fisheries [148]

Under South African legislation, it would be difficult to justify commercial utilisation without, for example, providing the local community with an alternative source of energy (see also further explanations below) [56]. Fuelwood, obtained mainly from natural woodlands, is said to be the primary source of energy used by households in most rural areas for cooking and heating. In some areas wood as a source of energy is almost completely depleted; in others it is under heavy pressure; or a third concern, some areas are heavily encroached by indigenous and alien plant species, and thereby limiting productive capacity of otherwise utilisable, especially agricultural land [152] where livestock is reared in 'High Altitude Acacia' areas (see Table 4-3).

Officials of the Department of Agriculture, Forestry and Fisheries [306] estimate that 60% of South Africa's population still makes use of wood as a primary source of energy. Verification of this information, by the population censuses carried out in 1996, 2001 and 2007 respectively, established that only 14-20% of the population makes use of wood as a source of energy; mainly for cooking and heating [153, 154, 155]. This research assumes that 20%, [153, 154] of the South African population makes use of wood resources from woodlands as their primary source of energy.

Based on the population censuses carried out in South Africa in 1996, 2001 and 2007, and additional research by von Maltitz and Scholes [156] residential energy needs of South Africans covered by wood resources may be expressed as follows [159, 157, 154]:

- For heating purposes up to 2007 and accounting for 14,9% of the population: between 40.9TJ and 231.5TJ, or the approximate equivalent of between 2.1 and 12.1Mt of wood.
- For cooking purposes up to 2007 and accounting for 19,6% of the population: between 53.9TJ and 305TJ, or the approximate equivalent of between 2.8 and 16.1Mt of wood.
- Total annual industrial energy consumption (mainly for heat) from biomass is 238TJ, or the approximate equivalent of 12.5Mt of wood.

The total amount of domestic energy from fuelwood is considerable and at least of the same magnitude as total biomass utilised for industrial purposes. Wood as energy source for the local population is obtained from living biomass, waste from commercial forestry plantations (of relative little importance) and deadwood collected from woodlands [157]. Figure 4-8 shows the current traditional supply and demand for wood as a type of energy in South Africa [40, 7, 142, 148, 158].

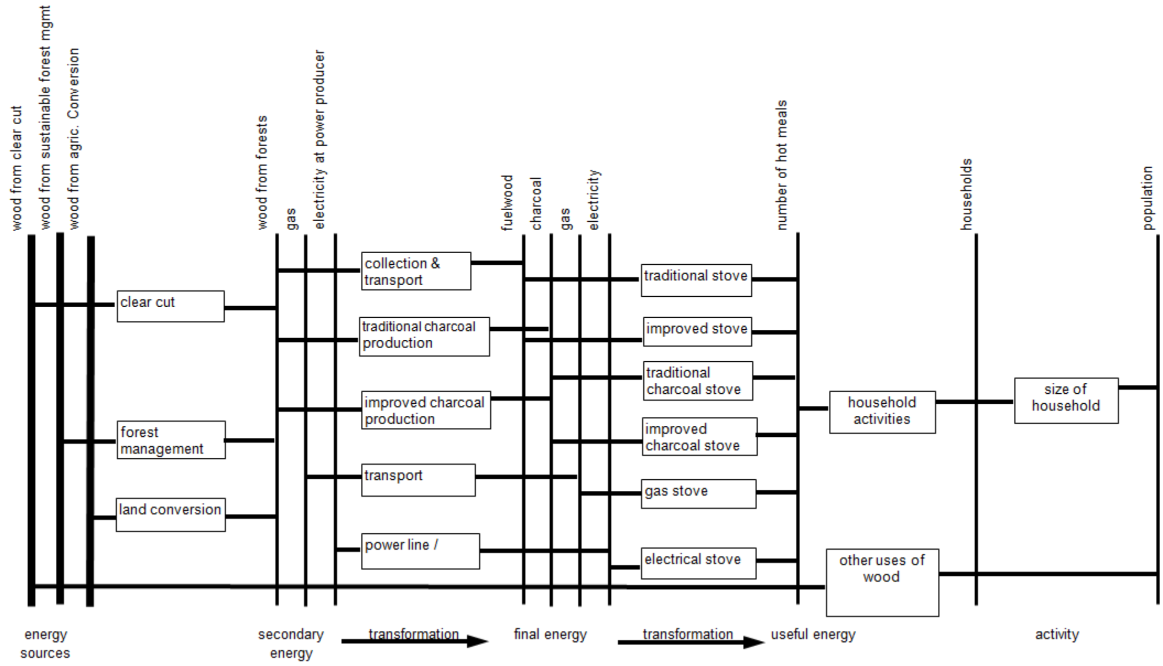

Figure 4-8 Energy reference system for traditional uses of wood in South Africa adapted from Ellgård *et al.* [158]

Woodlands on average produce deadwood at a rate of 1.5-2.0% of standing biomass per annum [159]. Local communities do not utilise this resource completely. However, it is questionable whether this wood is suitable for fast pyrolysis conversion and therefore not considered in this research. Von Malitz and Scholes [156] assessed that there is positive production of biomass from woodlands of 4% of standing woody biomass per annum.

4.1.4.1 Bush Encroachment

According to the Conservation of Agricultural Resources Act (CARA, Act 43 of 1983) some indigenous tree species (mostly *Acacia spp.)* pose a challenge for land management in South Africa. Bush encroachment in South Africa is mentioned in a similar context as it is in the Namibian case (sections 4.1.1 and 6.1.1) in this research. Bush is a potential feedstock to deliver bioenergy under the auspices of the South African Biofuels Strategy [7] and possible other uses. As under Namibian considerations, it is not the intension to explain the causes or dynamics of bush encroachment, but rather to establish the potential and total annual amount of biomass that may be available for conversion by fast pyrolysis.

Bush encroachment is said to affect the agricultural productivity and biodiversity of 10-20Mha of South Africa. [160, 161]. The 1996 vegetation map of Low and Rebelo [162] suggests that a total area of 3.4% or 41.5Mha of South Africa is subject to bush encroachment. The area includes bush-encroached patches and land invaded by alien plant species (some 10Mha); the proportions were however not scientifically assessed in further detail. The areas most affected lie in the Eastern Cape, Kwazulu-Natal, Limpopo, Mpumulanga, Northwest and Western Cape Provinces [117]. As is the concern in the Namibian case, the environmental threat posed by bush encroachment lies in its potential to induce land degradation, notably desertification over the affected parts of South Africa [163]. Ward [160] has recorded and summarised the extensive research done on bush encroachment dynamics in Namibia and South Africa since 1856. According to Ward [160], von Maltitz *et al* [156], Hoffmann [164] Palmer [165] and Watson [166], bush encroachment is an integral part of woodland dynamics, but if not controlled leads to loss of biodiversity.

Although the dynamics of bush encroached areas have been studied, data on physical inventory of these areas of South Africa is not readily available nor accessible. A number of indicative data was found based on satellite imagery, aerial photography, remote sensing and geo-referenced information systems [165, 167, 164, 168, 169 152]. Research using satellite imagery and aerial photographs has enabled the documentation of the rate of encroachment in many of the affected areas. The biomass quantities available from bush-encroached areas are expressed as "% of woody plant canopy cover" (Figure 4-7) or are indicated as "leaf area index" and should hence provide information about the size of the infested areas, their location, and to a limited extent their species distribution. However, to date, no substantial, all-inclusive evaluation has been undertaken to confirm and align the information obtained through satellite imagery and geo-referencing to actual stand- and/or tree-level inventory. Time series analysis established the annual growth or the degradation of land cover; the data is used in Chapter 5 and 6.

4.1.5 Biomass from alien invasive plants

South Africa has a long history of problem plants, which have been variably called 'weeds', 'pest plants', 'plant invaders', 'invasive plants' or 'naturalised exotics or aliens' amongst others. The first recorded control campaign against an alien plant species in South Africa was in 1860 [149]. The Conservation of Agricultural Resources Act (CARA, Act 43 of 1983) and its regulations declared about 50 species of "weeds" or "invader plants" in 1984. Also based on a comprehensive listing of weeds and invasive plants done in 1986, the Ministry of Agriculture implemented an amendment to the regulations of the CARA of 1983 the [170, 149] in 2001. The amendment to the regulations contains a comprehensive list of species that are declared weeds and invader plants which need control and/or elimination as per three categories, namely:

- *Category 1 species* (e.g. Triffid Weed, Lantana) are generally the 'worst offenders'. As declared weeds, they may not occur on any land or on any inland water surface throughout South Africa. This category of plants should be eradicated completely.

  Category 2 species (such as pine, wattle, poplar and gum) are also problematic but are more commonly grown for commercial purposes (section 4.1.3.2) or any viable and beneficial function, such as for woodlots, fire belts, building material, animal fodder and soil stabilisation. Where these species are to be planted, licensing is required and can only be undertaken in demarcated areas. An example is a registered and licensed timber plantation. The species are regarded as weeds outside of these demarcated areas, and landowners are required to take steps to control the species where they occur on their properties, for example, in the case of "wattle jungles", i.e. *Acacia mearnsii* (see also section 7.1.2.2).

- *Category 3 plants* (such as Syringas and Morning Glory) are generally ornamental plants, which may be retained, but no new planting or trade or propagating of these plants is permitted.

In 1995 the Government of the Republic of South Africa embarked on the 'Working for Water' Programme (WfW) to control invasive alien plants [152]. The WfW Programme proposed a 20-year clearing strategy at 750kha to be cleared per annum and approximately ZAR600M (million South African Rand) to be spent on clearing per year, excluding the impact of new invasion by alien plants. The Programme estimated that, in total, over 10Mha of invaded land in needs to be cleared. The cost per hectare varies depending on a number of factors such as the location, species and the density. WfW seeks to optimise its investment by extracting and utilising invading alien plant biomass resulting from clearing operations.

The assessed inventory of invasive plant species is limited to specific locations of the Eastern and Western Cape in natural forests and protected land. The inventory of alien wood invader plants, notably alien *Acacia* species, like *Acacia mearnsii*, is measured against the total estimated infestation in the Eastern and Western Cape and is as provided in Table 4-4 [304].

Table 4-4 Estimated total area of infestation and the corresponding inventory of wood biomass for assessed areas which are infested with alien wood species [304]

	Estimated total infestation (Mha) 1996/7	Assessed area infested (Mha) 2004	Foliage (Mt)	Branches <25 mm diameter (Mt)	Wood 25-50 mm diameter (Mt)	Wood >50 mm diameter (Mt)	Total potential Biomass available as feedstock (Mt)
Eastern Cape	0.1161	0.0767	1.2253	1.7862	2.3889	5.7574	11.1577
Western Cape	3.7274	0.0265	0.6914	1.1585	0.8878	0.9343	3.6720
Total	**3.8935**	**0.1033**	**1.9167**	**2.9448**	**3.2766**	**6.6917**	**14.8298**

The emphasis of the WfW programme lies in the elimination and eradication of Category 1 and 2 alien invasive plants where these are not wanted [171].Category 1 and 2 alien invasive plants (section 4.1.3.2) were focussed on, however, also limited to wood-based alien invasive plants (like *Acacia mearnsii*). Various aspects of work carried out under WfW were reviewed with the aim to use the cleared wood-based biomass to investigate which would have the highest potential as feedstock to produce bioenergy in South Africa. The WfW Programme achieved to clear and do follow-up clearing as summarised in Figure 4-9 until the 2007/08 financial year. After 2007/08 annual reports on the clearing of alien tree species no longer contained such detail.

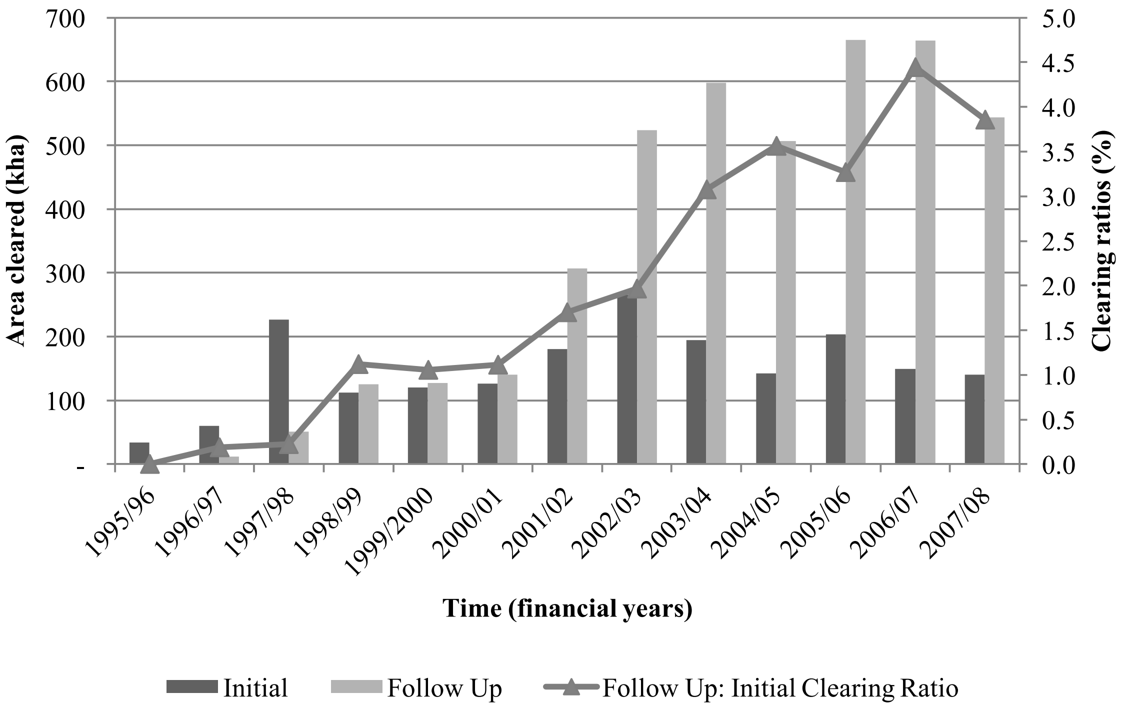

Figure 4-9 Areas (ha) invaded by alien plants which were cleared by Working for Water Programme in all nine provinces of South Africa, between 1995/96 and 2007/08 [176]

Up to 2003/04, the WfW programme had launched more than 300 projects concerned with clearing, harvesting and extraction of alien species from the various sites. As part of the WfW programme, wood processing industries were started. Seven "pilot projects" on a cottage industry basis in South Africa included the production of firewood and charcoal, fencing and other construction materials, furniture, and artefacts [176, 172, 173].

Three industrial projects were considered in 2001 which were the utilisation of the stems and heavy branches for the production of wood chips and charcoal (85% of harvested material), and the utilisation of leaves and berries for the production of organic fertiliser (15% of the harvested material) [174, 175]. However, it seems that the objectives of the WfW are too broad and that funds are lacking to consolidate the research and development work in terms of bioenergy where extracted alien invasive plant biomass is the feedstock [176, 177, 178].

Particularly, WfW has identified charcoal making as a viable option to create reasonable returns. However, WfW programme managers have cautioned that pollution and cost intensive industries would not be tolerated. Black Gold Forest Products and Zozithi Charcoal Project were the only two projects for which information was documented under the WfW programme. The projects utilised wood-based feedstock from alien wood species clearing operations to produce large quantities of charcoal, mainly for the domestic market. Black Gold Forest Products declared insolvency in 2007; whether Zozithi is still operational is uncertain.

4.1.6 Authorisation requirements to utilise biomass resources and establish bioenergy generation plants

The National Environmental Management Act (NEMA) [127] as amended [179, 286] presents environmental impact assessment guidelines for renewable energy projects as summarised in Table 4-5. Compliance to the NEMA attracts considerable costs which need to be taken into account when modelling bioenergy generation (section 5.4.1).

Table 4-5 Renewable Energy Authorisation Requirements [179]

Legislation and/or guideline	Aim of legislative measure
The Constitution of the Republic of South Africa, 1996 (Act 108 of 1996)	• Prevent pollution & ecological degradation • Promote conservation • Secure ecological sustainable development
National Environmental Management Act (Act 107 of 1998); included are the following 'sub'-acts: • Waste Act (Act 59 of 2008); and Waste Amendment Act (Act 26 0f 2014; Government Gazette No. 37714) • National Environmental Management Laws Amendment Act (Act 25 of 2014; Government Gazette No. 37713) • Air Quality Act (Act 39 of 2004) • Biodiversity Act (Act 10 of 2004) • Protected Areas Act (Act 57 of 2003) • Occupational Health and Safety Act (Act 85 of 1993)	After compliance to all requirements, provide authorisation to commence industrial activity, informed by: • Integration of the principles of environmental management • Principles of safeguarding biodiversity, air quality and emissions control • Effective waste management • Identification, prediction & evaluation of actual / potential impact on the environment • Potential effects are duly considered before actions are taken • Adequate & appropriate public participation • General compliance & enforcement.
The National Water Act (Act 73 of 1998)	• Issuing of water use licences in relation to extraction, storing, specific use of fresh water and disposed of contaminated water, including necessary consultative processes prior to licencing • General compliance & enforcement.
Water Services Act (Act 108 of 1997)	• Regulating the right of access to basic water supply and basic sanitation, and related matters at municipal level • General compliance & enforcement.
Hazardous Substances Act (Act 15 of 1973)	• Control of substances which may cause injury, ill-health or death • Defining of substances as hazardous in relation to degree of danger, prohibition/ control of trade, manufacture, use, operation, application and disposal • Provide for minimum requirements for handling, classification and disposal hazardous substances and/or waste • General compliance & enforcement.
Physical Planning Act (Act 125 of 1999)	• Promotes the structured physical development of South Africa at regional level
Development Facilitation Act (Act 67 of 1995)	• Provide for general principles governing land development throughout the country, at national level
Electricity Regulation 2006 (No. 4 of 2006), as amended by ERAA (Act 47 of 1999, as amended in 2007)	• Provide for a national regulatory framework for electricity supply industry, and makes the National Energy Regulator of SA the overseer and enforcer of the framework • Provides for minimum requirements for

Legislation and/or guideline	Aim of legislative measure
	registration & licencing of generation, transmission, reticulation, distribution, trade (or import/export) of electricity. • General compliance & enforcement.
Municipal Systems Act (Act 32 of 2000)	• Development at local level, including e.g. *Integrated Development Plans* (IDPs) and tariff setting • Regulates municipal service delivery and mechanisms for municipal service delivery • General compliance & enforcement.
Conservation of Agricultural Resources Act (No. 43 of 1983)	• Conserve agricultural resources, including soil, water and vegetation, but excluding weeds and invader plants • General compliance & enforcement.
Mineral and Petroleum Resource Development Act (No. 28 of 2002) (has only indirect relevance to fast pyrolysis operations)	• Provide for environmental management in prospecting and mining operations, but excludes provisions for extraction of coal, bituminous shale or other stratified deposits • Focus is on "petroleum" in any form occurring in the earth's crust • Provide for equitable access to and sustainable development of such resources • General compliance & enforcement
Road Traffic Management Corporation Act (No. 20 of 1999), and National Roads Act (No. 93 of 1996) (has only indirect relevance to fast pyrolysis operations, but directly to logistics concerned with such operation)	• Provide for cooperative & coordinated strategic planning, regulation, facilitation & law enforcement in respect to road traffic, and includes e.g. • Protection of road infrastructure & environment • Ensuring overall quality of road traffic service provision (security, safety, order, discipline, mobility) • General compliance & enforcement.
Spatial Planning and Land Use Management Bill (SPLUMB) [B14 – 2012] (the Bill is not yet promulgated into an Act)	• To confirm & regulate the role of municipalities in land-use planning and management • To ensure the system of land-use planning and management promotes socio-economic inclusion • Provide for sustainable & efficient use of land.

4.2 REVIEW OF BIOMASS RESOURCE MODELS

4.2.1 The Policy Analysis System (POLYSYS)

The Policy Analysis System (POLYSYS) modelling framework was developed to simulate changes in policy, economic or resource conditions and estimate the resulting impacts for the U.S. agricultural sector [180, 181, 182]. POLYSYS is structured as a system of interdependent modules simulating crop supply for 305 production regions; crop demand and prices; livestock supply and demand; and income in the US agricultural sector. The POLYSYS modelling framework can be expanded to include analytical capabilities to endogenously consider (a) a wide variety of region-specific crop rotations and management practices; (b) environmental impacts; (c) production of energy crops characterised by multi-year production cycles; (d) crop derivative products such as fats and oils; and community economic impacts.

4.2.1.1 C1. Link to economic theory and national policy indicators

POLYSYS anchors its analyses to a published baseline of projections based on official data published by US authorities. The projection periods span 5-10 years. The economic theory underlying the POLYSYS is not clear, however is assumed to be a sector model, focussed on agriculture. POLYSYS is based on a number of simulations which provide projections, both baseline and best case/worst case projections on a number of variables relating to the agricultural sector.

In the Namibian context, neither baseline data nor baseline projections exist. This means that baseline data needed to be established by this research for a wood-based biomass resource model. The baseline data was used to establish baseline projections (section 4.2.1.5). In the South African context, baseline data exists though at an aggregated level (section 4.1.3). However, no baseline projections exist.

4.2.1.2 C2. Spatial considerations

At its core, POLYSYS is structured as a system of interdependent modules simulating crop supply for 305 agricultural production regions. The data collected in the respective modules include national crop demand and prices, national livestock supply and demand, and agricultural income. Other modules are available within the POLYSYS modelling framework to expand its analytical capabilities. The POLYSYS provides lessons relating to the following:

- The biomass resources available in Namibia and South Africa need to be considered independently and according to the geographical and political regions respectively.

- For each, Namibia and South Africa respectively, the type and quantity of wood-based biomass resource must be determined separately.
- The economic impact of utilisation of wood-based biomass resources available to certain communities need to be considered in both cases. The total available wood-based biomass resources available to fast pyrolysis will reduce by the amount of resources which are used currently, and is likely to be used in future by a community depending on such resource.

4.2.1.3 C3. Dynamic features

In the Namibian context, the model as proposed by this research for wood-based biomass resources may not be the framework model itself. The main reason is that POLYSYS is a policy analysis tool. However, there is a great lack of policy governing biomass resource production and use in general in Namibia. In the South African case, policies governing biomass resource production and use exist (section 4.1.3), but the scope of this research is on production of wood-based biomass resources and the use thereof for fast pyrolysis only. The impact of use of wood-based biomass for fast pyrolysis and ultimately bioenergy is seemingly very small; no major policy impact is expected in Namibia and/or South Africa; therefore limiting the usefulness of the principles of POLYSYS for this research.

4.2.1.4 C4. Link to other sectors and land use issues

POLYSYS focuses on the variables which influence the agricultural production system in the USA. The variables may also originate from sectors other than the agricultural sector. In the Namibian and South African context, the linkage to other sectors beyond agriculture is important. The principles underlying the POLYSYS framework model are useful to assist with establishing the relationship between the agricultural sector (encompassing biomass production and use) and other sectors, like; supply to the agricultural sector, markets for agricultural products (in this case including products from fast pyrolysis), and the energy sector. The POLYSYS model can be adopted and adapted to encompass the sectoral relationships in the Namibian and South African case.

4.2.1.5 C5. Model and data availability and model adjustments needed

POLYSYS is a US data and policy based model and as such not useable in the Namibian or South African situation. The model structure is also not adjustable to that of the Namibian and South African agricultural and/or energy sector. However, the principal scenarios and the type of data underlying the POLYSYS model are of importance. Using the principles of POLYSYS and the baseline as a starting point, can introduce a wide variety of exogenous shocks and simulate the resulting impacts for biomass supply and demand and agricultural income (section 2.6).

The data and principles of the POLYSYS model to be used in the Namibian context, would include encroachment bush only. In the Namibian context, the relationship between bush encroachment and livestock production systems and output needed investigation [265, 88, 102, 98, 116] (section 6.1). Furthermore, economic impact for community development is very important in the Namibian case.

The data and principles of the POLYSYS model used in the South African context include the following:

- Biomass endogenously considered in the conceptual model (section 2.6) include commercial forest waste and residues, residues and waste from timber mechanical processing, natural woodland, bush encroachment, alien plant species control. Agricultural production residues were not considered for this research as the available data is too aggregated and their source destination is uncertain.
- To model biomass commodities in South Africa, the conceptual model simulates the impacts of changes from the baseline upon commercial timber supply and demand variables including planted and harvested land, yield, production, exports, costs of production, current demand, government programme outlays, and net realised income. The model simulates supply and demand for each timber commodity, and is dependent on its geographical region.

The results of wood-based biomass data and resource modelling and the resulting potential of biomass resources use in Namibia and South Africa are presented in Chapter 5 and 6 respectively.

4.2.2 The conceptual model of vegetation dynamics in semiarid Highland savannah of Namibia, with particular reference to bush thickening by *Acacia mellifera*

The conceptual model of vegetation dynamics (abbreviated as CMVD) proposes a state-and-transition model for vegetation dynamics in semiarid Highland Savannah of Namibia [301], with particular reference to bush thickening by *Acacia mellifera*, i.e. only one type of wood-based plant species which has been identified as indigenously invasive in a relatively small part of Namibia.

4.2.2.1 C1. Link to economic theory and national policy

Although a model with its origin in Namibia, the CMVD does not link economic theory and national policy. The CMVD is a conceptual model built on states of bush and grass interactions. The CMVD conceptualises and describes the dynamics, mainly influenced by climatic events, of how a predominantly 'bush state' can transit to become a predominantly 'grass state'; and vice versa. The CMVD calls for models with the aim to describe vegetation dynamics by considering theory of maintaining an ecological balance, not an economic equilibrium. However, better understanding the intrinsic interaction between ecology and economic output would assist farmers in particular. With better management of the land and its biomass resources, livestock and human productivity, farmers could essentially grow economic output, yet maintain ecological sustainability (Table 4-1). This means, controlling bush encroachment, maintaining appropriate stocking rates of livestock, recognising the importance of climatic events, and taking potential management actions, induces and/or sustains a "stable vegetation state". A stable vegetation state would be where perennial grasses dominate the landscape, 'decorated' with indigenous wooded plants. An unstable vegetation state would constitute land degradation, e.g. by bush encroachment or desertification induced by prolonged droughts.

4.2.2.2 C2. Spatial considerations

The CMVD considers only one bush encroachment species, i.e. *Acacia mellifera* spp. *detines* and is limited to the Highland Savannah of Namibia. The research underlying the CMVD is limited to an area of approximately 20kha, which is very small in comparison to the area covered by bush encroachment (approximately 29 Mha) and the types of species declared as bush encroachers in Namibia.

The CMVD is useful to describe bush encroachment growth and inventory dynamics in Namibia (section 6.1) and South Africa (section 6.2.3). Beyond that, the CMVD was not used.

4.3 REVIEW OF LITERATURE ON FAST AND SLOW PYROLYSIS TECHNOLOGY IN NAMIBIA AND SOUTH AFRICA

The objective of this section is to review literature on thermo-chemical conversion technology, and in particular wood-based biomass slow pyrolysis. The emphasis is on technology that is or was available in Namibia and South Africa because it is important to understand whether it is possible to operate the more advanced fast pyrolysis technologies in Namibia and/or South Africa.

Apart from the AGODA production system [191] which was developed in Namibia in the 1980s, technological advancement with regard to Namibian fast or slow pyrolysis technology has not taken place; in Namibia the "Namibian Bush Drum Kiln" is used by and large (Table 4-6) since approximately 2000. Numerous slow pyrolysis systems were developed in South Africa since the 1980s, some of which are still in use. Technological development for slow pyrolysis systems in Namibia and South Africa coincided until 1990. In addition and where relevant, further research and development of secondary production and use of the primary products obtained from operating fast (if applicable) and slow pyrolysis systems will be discussed. With the abolishment of the apartheid regime in South Africa, research and development work in the field of biomass conversion was more or less suspended in 1994 [318]; more important socio-economic development issues like poverty alleviation and job creation had to be addressed. This e.g. in part explains why data on physical and chemical properties of Southern African wood-based biomass was ceased to be published. A similar situation was experienced in Namibia for the period 1990 until the launch of the National Commission for Research, Science and Technology in 2013 [183].

For the purposes of augmenting literature review on technology in this research several study tours were undertaken to Namibia and South Africa in the period 2003 to 2008 respectively; efforts were made to find out whether fast pyrolysis systems exist in Namibia and South Africa.

4.3.1 Review of literature on fast pyrolysis conversion technology

An entrepreneur, a chemical engineer by profession, attempted to pilot a self-designed entrained flow fast pyrolysis system in South Africa. The idea was to pyrolyse saw dust and wood chips which were a by-product of sawmilling industries in the Limpopo Province, South Africa [184]. The pilot system failed. As explained by the entrepreneur [184], seemingly due to too high moisture content (above 25wt.%) of the feedstock which exerted extreme high pressure on the system, subsequently causing the reactor to explode. The project was supported by the provincial government and in total cost ZAR0.3M in 2004/05. A second attempt to set up a fast pyrolysis system was not made [185].

A South African company, based in Johannesburg [28], is engaged in producing fluidised bed fast pyrolysis plants, which are exported to European based companies involved in fast pyrolysis conversion for energy production. The design and technology was patented by South Africans. However, the technology itself is not used nationally.

Kinetics and thermal decomposition mechanisms for the fast pyrolysis of plant biomass and its constituents have been extensively studied [66, 186, 187,]. Few studies have focused on *in situ* upgrading of bio-oils to generate chemicals [188, 189]. However, the latter subjects will be pursued further in this research (Chapter 7).

4.3.2 Review of literature on slow pyrolysis conversion technology

Industrial charcoal-making based on slow pyrolysis has a comparatively short history dating back about 150 years [64, 63]. Its principles may be outlined as follows:

- Relatively high investment costs
- Intensive use of labour saving equipment and devices
- Efficient recovery of liquid and/or gaseous co-products for captive and commercial use
- Wide range of raw material usage, including forestry, agricultural and municipal waste
- Such undertakings necessarily involve prior feasibility studies, qualified plant design and organisation of logistics (norms, standards/quality of products; harvesting, storage and transportation).

Several live examples of slow pyrolysis plants (photographs below) which use wood biomass or as feedstock are still operational in several industrialised and emerging economies. These include equipment which is used among the following companies, globally:

- Germany – Chemviron Carbon GmbH, now known as PROFAGUS uses the Reichert Continuous Retort System; recovery of wood spirit, liquid smoke, lump charcoal and activated carbon; feedstock size optimally at ca. 5 cm x 5 cm x 25 cm;
- Latvia – e.g. Vertical & interchangeable stationary retorts developed by Latvia State Institute of Wood Chemistry [190]; lump charcoal and heat recovery; feedstock size from 5 cm x 5 cm x 25 cm to up to 15 cm x 15 x cm x 2400 cm;

- Belgium, USA and Canada – e.g. Nichols Herreshoff Carboniser; recovery of charcoal granulate, steam production and energy recovery; feedstock size preferably smaller than 2,5 cm x 2,5 cm x 10 cm;
- South Africa – e.g. AGODA continuous retort system – inactive [191], CG2000 retort system [192, 193], beehive kilns [73] made of masonry; Armco Robson [194, 195] kilns made of steel; recovery mainly of lump charcoal; heat and pyrolysis liquids recovery only with AGODA process; feedstock size from 5 cm x 5 cm x 25 cm to up to 15 cm x 15 x cm x 2400 cm. The Nichols Herreshoff pyrolyser was used by Charka (Pty) Ltd [196] in Piet Retief, South Africa until approximately in 2000.

The AGODA and CG2000 retort processes have possibilities for automation and heat and energy recovery possibilities. The South African industrial type kiln processes are feedstock intensive with conversion ratios of between 10 to 30% as well as the emission of 80 to 90wt% of feedstock as smoke-like wood gases to the atmosphere. No filter systems are available in the processes and therefore, these systems cannot be considered environmentally friendly. This was indicated as a problem in the assessments done for the initial Working for Water Programme in Mpumulanga province in 2002 [197].

For this research, extensive visits to various producers of charcoal in Namibia and South Africa were undertaken. The aim of the visits was to establish the status of pyrolysis technologies and deployment. Also, the visits were used to investigate whether a potential exists to deploy fast pyrolysis technologies in the charcoal manufacturing sector or whether companies and/or persons could be identified who are interested in using improved pyrolysis technologies.

Table 4-6 is a result of the interviews and investigations conducted where a certain technology is used in Namibia and South Africa. A thorough desktop study to this end was not possible as producers of charcoal were not prepared to commit to information requested via telephonic discussion or written requests (electronic mail or via post mail). The investigations of various processes were conducted on a regular and follow-up type of basis between 2001 and 2007.

Table 4-6 shows the various slow pyrolysis processes as employed industrially. Most of these processes are still in operation; where a process is dormant or was suspended, this is indicated in the Table.

Table 4-6 Summary and Status of Slow Pyrolysis Systems developed and used in Namibia and South Africa [own investigations; 234, 190, 191, 193, 194, 195, 196, 198, 198, 199, 200, 201, 202, 203, 204, 205, 206, 308, 198, 218, 221, 207, 207]

Type of Apparatus	Conversion factor (wet wood to charcoal)	Reten-tion time	Equip-ment sizes operated	Feedstock type and size	Co-Product Recovery	Quality of Product	Product Consis-tency	Reli-ability	Maintenance requirements	Investment Costs
Earth Mould Kiln (various African countries, stopped being used in South Africa)	11:1	72 hours	-	Wood pieces	None	Poor	Poor	-	-	Very low
Namibian Bush Drum Kiln	6-11:1	24 hours	1.36 m^3	Wood pieces	None	Adequate	Adequate	-	Very low	Very low
Brazilian Beehive Kiln (South Africa)	6-7:1	1 week	70 m^3	Wood poles	None	Good	Adequate	Good	Low	Medium to low
Armco Robson Kiln (South Africa, Mozambique)	6-7:1	60-70 hours	±27 m^3	Wood poles	None	Good	Adequate	Medium	Low	High
VMR Box Batch Retort (Netherlands, stopped being used in Namibia and South Africa in the 1980s)	3-4:1	6-12 hours	15 m^3	Wood pieces	Heat recovery	Medium	Medium	Medium	High	High
AGODA Continuous Retort (stopped being used in Namibia and South Africa in mid-2000s)	3-4:1	0,3 th^{-1}	±25 m^3	Wood pieces or chips	Heat recovery, pyroligne ous liquids	High	High	High	Medium; approx. 8 yrs life time	Medium
Nichols Herreshoff Carboniser (USA, Canada, Germany, Belgium, stopped being	4:1	1-4 th^{-1}	±100 m^3	Wood chips	Heat recovery	High	High	High	Very high	Very high

Type of Apparatus	Conversion factor (wet wood to charcoal)	Reten-tion time	Equip-ment sizes operated	Feedstock type and size	Co-Product Recovery	Quality of Product	Product Consis-tency	Reli-ability	Maintenance requirements	Investment Costs
used South Africa)										
Constantine Batch Retort (operations stopped in South Africa in 1990s)	3-4:1	6-12 hours	15 m^3	Debarked Wood chips	Heat recovery	Very high	Very high	Not known	Not known	Very high
Gaylard Batch Retort (operations stopped in Namibia in late 1980s)	3-4:1	6-12 hours	±25 m^3	Small particles, wood chips or wood pieces	Heat recovery	Very high	Very high	High	Very high	High
Tilting Batch Retort (unknown if still operational)	4:1	6-12 hours	±15 m^3	Wood pieces	Heat recovery	Very high	Very high	Not known	Not known	High
PYRO-7 kiln (only a prototype is available, but not operational)	3-4:1		±350kg/h	Debarked wood chips	None	High	Not known	Not known	Not known	Not known
CG2000 continuous retort (operational in South Africa; operations planned for Namibia)	3-4:1	6-12 hours	±25 m^3	Wood poles or pieces	Heat recovery	Very high	Very high	Very high	High	High

Photograph 4-1 **AGODA Continuous Slow Pyrolysis System at Piet Retief, South Africa; visited December 2006**

Photograph 4-2 **(left) CG 2000 Batch Retort System; (right) charring pot, which is inserted into the heat exchanger of the retort system, left. Carbo Group, Greytown, South Africa; visited December 2006**

Photograph 4-3 **Masonry Beehive Kiln in operation near Pietermaritzburg, South Africa; Operated by E&C Charcoal; visited December 2006.**

Photograph 4-4 **Armco Robson Steel Kiln in operation near Pietermaritzburg, South Africa; Operated by E&C Charcoal. Two kilns are connected to each other, and share one exhaust system; visited December 2006.**

Photograph 4-5 **Namibian 'Charcoal Drum' Kiln in use; this system is the only operational charcoal manufacturing equipment still in use in Namibia. Photo taken near Grootfontein, Namibia; August 2014**

Photograph 4-6 **Namibian 'Charcoal Drum' Kiln being discharged after charcoal is totally cooled. Jumbo Charcoal (Pty) Ltd. Okahandja, Namibia; visited April 2007**

4.4 REVIEW OF BIOMASS THERMO-CHEMICAL CONVERSION MODELS

Many models to describe thermo-chemical conversion of biomass resources were found, but after preliminary assessment only two models were found to be of particular interest to this research which are discussed in more detail below. The two models are; Bioenergy Assessment Model (BEAM) and Homer/SABRE model. The Namibian-Finnish cooperation project "Energy Policy, Regulatory Framework and Energy Future of Namibia" [58] considered an energy system model for Namibia; however the project did not consider biomass at all as a source of energy in the model. It is difficult to assess the usefulness of the model for this research as in addition, the model is for the use by authorities in a policy environment only.

Another 'model' was found to be applicable, describes an approach that establishes factors influencing the effectiveness, reliability and scalability of biomass-to-energy conversion projects. The latter being the "black box" approach [208] to project evaluation and risk assessment.

4.4.1 The Bioenergy Assessment Model (BEAM)

The Bioenergy Assessment Model (BEAM) is a comprehensive bioenergy model established by an IEA Bioenergy Agreement Task in 1998 [209, 210]. The model consists of a collection of spreadsheets, called modules. Each module models the cost and performance of a discrete part of an integrated bioenergy system. A user defines a basic bioenergy system for evaluation by selecting a feedstock, the required product and a conversion route. Once defined, BEAM should calculate technical and economic parameters for the system at a specific capacity based on cost and performance characteristics typical for the feedstock and technologies used. This "generic system" can normally be accepted as the user can adapt the basic system to more specific cases by changing variables as required.

4.4.1.1 C1. Link to economic theory and national policy indicators

BEAM is an integrated model that takes account of economic theory in terms of its costing approach. The costing approach is integrated into each module. Policy indicators do not form part of BEAM. The lack of policy analysis possibilities in BEAM is not a draw-back as BEAM strictly focuses on techno-economic analysis of thermo-chemical conversion.

4.4.1.2 C2. Spatial considerations

BEAM is limited to conversion of European and North American feedstocks and costing approach. As the modules of BEAM make provision for costs associated with feedstock to be transported from one location to another where thermo-chemical conversion would take place, spatial considerations are not needed. BEAM can embrace that feedstocks originate from different locations to one thermo-chemical conversion plant. Bioenergy cost assessments end where a pyrolysis product is produced and stored prior to market delivery. The latter principle is also embraced by this research.

4.4.1.3 C4. Link to other sectors and land use issues

The principles of BEAM may be of use to model an integrated bioenergy system as proposed by the conceptual framework to ensure appropriateness of selected technology and are discussed in Chapter 8.

4.4.1.4 C5. Model and data availability and model adjustments needed.

This research embraces the approach of BEAM without necessarily using the module for explicit calculations – these would have to be done on a case-by-case basis.

The underlying principle of BEAM is useful to this research, especially as BEAM is built on spreadsheet modules. However, BEAM as such cannot be used by this research. The modules on which BEAM is built need adjustments (section 4.4.1.4.1). This is described below and discussed in more detail in Chapters 5, 6, 7 and 8. The results of the modelling process are presented in Chapter 9. The model adjustments are required include the modules; feed production; feed pre-treatment and feed conversion.

4.4.1.4.1 Adjustments to the feed production module

BEAM's feed production module covers the cost and performance of feedstock production and delivery to the feed processing plant where the energy product will be made. The downstream limit of the feed production module is the arrival of the raw biomass at the feed processing plant, immediately before unloading.

BEAM's feed production module is based on biomass originating from Europe or North America. Wood-based biomass species from Southern Africa are not considered. The costing for Namibian and South African feedstock need adjustments (Chapter 8).

In the Namibian case, feed only pertains to encroachment bush. A number of factors may influence especially the cost of the feedstock, notably harvesting methods and transport. In the South African case, feed would include commercial forestry residues, wood processing industry waste and/or woody biomass obtained from bush encroachment and invasive alien plant species. The whole tree approach for woody biomass from encroachment bush and wood-based alien plant species control is used.

The feed production module of the bioenergy model of this research factored the adjustments into the module (Chapter 8).

4.4.1.4.2 <u>Adjustments to the feed pre-treatment module</u>

BEAM covers the reception, storage, handling and pre-treatment of the delivered feedstock so that it is supplied to the specified conversion technology in a suitable form. The downstream limit of this module is immediately before the prepared feedstock enters the reactor feeding mechanism of the specified conversion technology.

As BEAM is based on feedstock from Europe and North America, the pre-treatment costs for Namibian and South African feedstock have to be adjusted. The latter feedstocks are all wood-based and the densities of these are substantially different from those in Europe and North America.

Feedstock will arrive in random sizes to the conversion plant. Depending on the fast pyrolysis conversion process, feed pre-treatment involves cutting and/or milling/grinding to size, sifting and drying to a certain moisture content level as determined and required by the conversion module to deliver a pyrolysis product to specification. The feed pre-treatment module of the bioenergy model of this research has factored the adjustments into the module (Chapter 8).

4.4.1.4.3 <u>A feed conversion module</u>

BEAM covers the conversion of the prepared biomass feedstock into the selected energy product. The downstream limit of this module is immediately before export of the energy product. Thus electricity generation ends at the grid connection terminal; liquid fuel production ends with the liquid in buffer storage; and heat production excludes the heat supply network.

BEAM is based on socio-economic needs pertaining to Europe and North America, and therefore adjustments are required. Heat production in the Namibian and South African case are limited to the needs by an individual or at corporate level (e.g. hot water production of hostels or hospitals); no infrastructure exists that would enable bulk heat supply to a whole community. The fast pyrolysis conversion module of this research ends with bio-oil in buffer storage. Slow pyrolysis processes on an economic viability basis only serve as comparative process to fast pyrolysis (Chapter 9).

In both the Namibian and South African case, the feed conversion module or the technology proposed to be used, involves fast pyrolysis processing. The feed conversion module of the bioenergy model of this research has factored the adjustments into the module (Chapter 7, 8 and 9).

4.4.2 Homer and SABRE-Gen Biopower model

In addition to BEAM, the Homer and SABRE-Gen Biopower model was found. From first indications it seemed that the Homer and SABRE-Gen Biopower as used by the South African national power generator and transmission corporation – ESKOM – would be able to cater for the South African situation. This specific model is aimed at the evaluation and assessment of 'bio-power' technologies, for their implementation in South Africa. The model seems to use various types of biomass resources as feedstock, which includes wood-based residues, agricultural residues and grasses. Although links on the worldwide web were found of this model's usefulness in South Africa, information on whether it was actually implemented could not be found [51, 211, 212, 213]. It seems that certain modules are not accessible to the public made it redundant for the purpose of this research. As cited on the websites offering information on the model, the aim is to solely produce power by using a gasification thermo-chemical process.

In 2005/06, Eskom investigated the possibility of using biomass as a source of energy for electricity grid-supply whilst also planning to pilot new technology aimed at providing rural power in a remote area in the Eastern Cape. This technology, a gasifier system [283], was to use waste from a rural sawmill to generate power and to provide electricity to support the creation of business ventures in the area. The system was expected to be launched towards the end of 2006, however, to date no further information has become available. All available public documents cited discuss the planning the project without providing information whether the project was actually successfully launched and/or whether it is still operational.

4.4.3 The "Black-box" approach to project evaluation and risk assessment

Slow pyrolysis projects are undertaken in Namibia and South Africa on a regular basis. Fast pyrolysis is a new concept which was introduced to South Africa around 2006/2007 only. At the moment an experimental scale fast pyrolyser is operational at Stellenbosch University, South Africa [312]; a pilot scale fast pyrolyser was built at University of Pretoria, South Africa [214]; a manufacturer of fluidised bed fast pyrolysis equipment is operational in Johannesburg [28], South Africa; and possibilities to import fast pyrolysis technology to Namibia and South Africa exist too. What all of the latter have in common, is that fast pyrolysis technology has not been seen working on a commercial scale. In addition, project evaluation and risk assessment for existing slow pyrolysis processes are largely lacking. Although developers of the novel fast pyrolysis technology may be enthusiastic to sell it, potential takers or financiers of such novel technology need to be able to assess the economic and environmental sustainability and risks associated therewith. At the same time, scaling an experimental fast pyrolysis project to the level of prototyping or even commercial operation bears considerable risk in general and operational evidence is not documented as yet.

The approach proposed by the "Black-Box" [208] is valuable to project evaluation and risk assessment of fast pyrolysis projects proposed by this research. Experiments to establish feedstock behaviour and produce bio-oil (Chapter 7) were carried out in a 150g/h fluidised bed fast pyrolyser. However, the commercial feasibility and viability of fast pyrolysis in the Namibian and South African context is based on a commercial costing approach (Chapter 8).

The success to "sell" fast pyrolysis technology to generate bioenergy in the Namibian and South African context needs a structured approach and the ability to identify areas of risk (environmental, socio-economic); to propose technical design modifications; and to allocate responsibility so as to create greatest possible comfort among role players and/or stakeholders in the light of perceived risk. The structured approach as suggested by this research is diagrammatically represented by the "Black-box" approach (Figure 4-10).

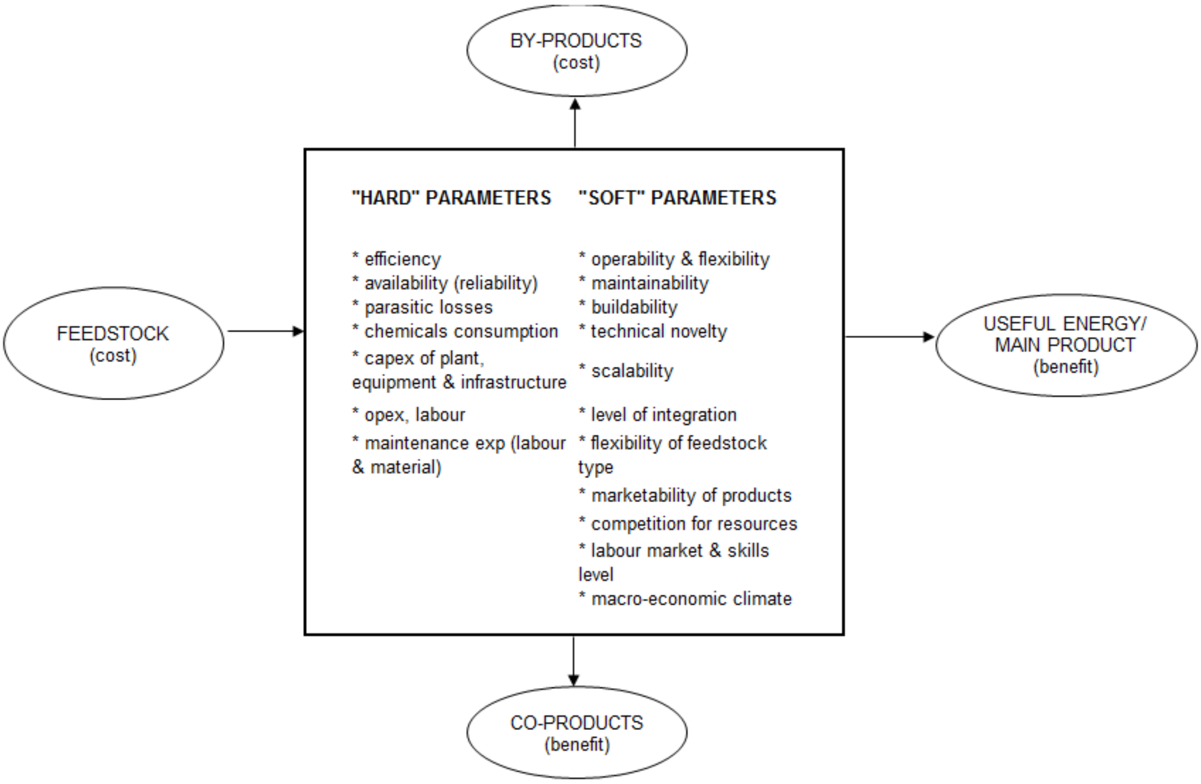

Figure 4-10 Black-Box approach to project evaluation and risk assessment [adapted from 208]

The factors that receive specific attention in this research relate to; efficiency, availability, chemicals consumption, capital expenditure, operational expenditure, maintenance, operability and flexibility, maintainability, buildability, technical novelty, and scalability. Competition for resources, labour market and skills, and macroeconomic climate (including social issues) are adjustments to the original "Black-Box" approach [208] as shown in Figure 4-10, and also mentioned and/or discussed in chapters 1 and 2. Issues like parasitic losses, level of integration and flexibility of feedstock type are mentioned, but not discussed in detail. The "Black-box" approach is the basis on which Chapter 8, and 9 were built.

The "Black-Box" approach characterises a financial model (based on the hard parameters), in summary, as follows:

- Selection of technology
- Project development costs
- Costs of the site, insurances, working capital and contingency allowance
- Allowance for inflation and taxes
- Gives internal rate of return (IRR) and net present value (NPV), cashflow and cover ratios

(i.e. the ratio of net project revenue to debt service costs) on project investment.

The model invariably involves much iteration before a satisfactory combination of project parameters is assembled. Selected fast pyrolysis projects were assessed with project costs including; development costs; and site, insurances, working capital and contingency allowance. The model derived by this research allows for inflation and taxes, and gives NPV, cashflow and cover ratio on project investment. The model was solved in MICROSOFT EXCEL® and EViews®8 and was used to find an optimal combination of the type of income and cost factors.

4.5 LITERATURE REVIEW ON MARKET POTENTIAL FOR FAST AND SLOW PYROLYSIS PRODUCTS

This section provides a review of literature relating to market potential for mainly fast and slow pyrolysis products; market potential specifically for fast pyrolysis products is mentioned if/when applicable. Based on the information provided in section 4.4.3, prior markets for fast pyrolysis products are assumed to be non-existent. To therefore establish markets for fast pyrolysis products, existing markets of slow pyrolysis products are investigated first. The emphasis is on South Africa as main market, including information on market developments over at least the past 20-30 years.

4.5.1 Market developments of slow pyrolysis products in South Africa

4.5.1.1 Charcoal

Until Namibia's independence in 1990, South Africa and Namibia (formerly known as Southwest Africa) formed one common market. Little up to date information was available on the slow pyrolysis industry, commonly referred to as the charcoal manufacturing industry in South Africa [215, 216]. Until 1982 Emrich [70] confirms that comprehensive slow pyrolysis data rarely appeared since the 1940s and much of the information is contained in specialised collections only, owned by private individuals [217]. Pioneering work was accomplished in 1982 when Gore compiled a compendium of charcoal production and properties in South Africa. The reports by Gore [218] and Bennie [216] summarised the status of the charcoal manufacturing industry in South Africa in general at the time. Charcoal production in South Africa was said to have increased by 30% per year between 1976 and 1982 [215]. The total charcoal production in 1981 was 76.1kt. Between 1982 and 1985 charcoal production had increased by about 47% per annum and soared to 206kt in 1983 [218]. The Bennie report [215] also noted that 2kt per annum of activated charcoal was manufactured from apricot and peach stones in the Cape Province.

Activated carbon in other literature cited plays an important role with regard to its demand in the industry, but processing of activated carbon is less extensively mentioned [308, 309, 216, 220].

Although a detailed cost breakdown was provided by Bennie [216] for the various types of slow pyrolysis conversion processes in 1982, these were found to be of no real value to this research. None of the listed slow pyrolysis technologies operational in 1982 still exist. The findings of the studies of Bennie [216] and Gore [218] culminated in a national conference on charcoal manufacturing in South Africa with the aim to better coordinate the charcoal manufacturing sector and make it more competitive. As a result of that conference, the South African Charcoal Manufacturers Association (SACMA) was formed [219] in 1986. The aim of the Association was to:

- Foster, promote and coordinate the manufacture and marketing of charcoal and its associated products in South Africa;
- Promote and protect the interests of manufacturers of charcoal; and
- Promote, support and oppose any legislation or other measures affecting the industry and the interests of the members of the Association.

The SACMA was re-launched in 2006 after having been dormant for more than 10 years.

Gore in 1982 [218] further compiled data from analysis and yields of non-condensable pyrolysis gas from various commercial grade charcoals. This data was intended to inform on gasification of charcoal for powering engines or generators. The data seems not to have been put to use at the time. It would have been more interesting if measurements of the non-condensable pyrolysis gas of various raw materials or feedstocks from the various retort processes could have been made. This data seems to be lacking even to date.

In 1983, waste materials generated from the pulp and paper industry were considered for charcoal production or as replacement for boiler coal [220]. The amount of usable plantation waste, bark, chip fines and fibres generated and to be used as replacement was close to 130kt per annum.

In 1985 it was reported [221] that the charcoal sector was facing severe competition within the timber industry. The reasons cited were that:

- due to expanding markets, the availability of large quantities of cheap timber used for charcoal manufacturing ceased to exist. Other uses for plantation waste were developed which resulted in greater competition for a relatively fixed amount of available timber;
- the latter effect was a steady increase in the market prices of all types of timber which lead to pressure on processors to achieve greater efficiencies in conversion and for them to investigate alternative sources of raw material;
- at the same time that both above had to be achieved, there was pressure to meet tight physical and chemical specifications and consistency of quality. [221]

In 1986, the National Timber Research Institute [222] reported that the charcoal industry was in need of quality standards for charcoal and charcoal briquettes. A committee was formed which formulated a specification subsequently published by the South African Bureau of Standards (SABS); specifications 1399-1983. Gore in 1983 [220] reported that advanced binding technology for the manufacture of charcoal briquettes were to be considered in order to obtain net gain from converting forest plantation waste and bark to charcoal. In 1985 Minnaar [199] reported of research work on binding techniques and agglomeration technology developments and introduced his findings which were in majority based on agglomeration of coal, anthracite or mineral fines but rendered valuable information for charcoal fines agglomeration [220]. Minnaar patented the process whereby commercial equipment would be available to upgrade materials having in excess of 90% fixed carbon without employing conventional heating processes to reduce the volatile content. Minnaar claimed that he was the sole holder of this superior technology worldwide. The products were produced by Solid Fuels of South Africa (Pty) Ltd in cooperation with Minimar Technologies AG (the company of Minnaar). The work of Minnaar provided Solid Fuels with contracts for producing charcoal briquettes which are sold in South Africa and elsewhere in the world still today. The total demand for briquettes from South Africa as reported by Minnaar is in excess of 100kt per annum henceforth.

The Council for Scientific and Industrial Research (CSIR) in South Africa invited interested parties to a strategic planning workshop on *'Use of charcoal fines as a soil conditioner in South Africa and South West Africa'* in 1985. Information presented at the workshop is based on research carried out by Kishimoto and Suguira in Japan [223]. Kishimoto carried out research on the fine charcoal's suitability as soil conditioner [224]. The advantages of the possible utilisation of charcoal as a soil conditioner in South Africa were cited to be that:

- charcoal improves water retention of the soil;

- charcoal improves root development;
- charcoal could increase pH levels of acidic soils and CO_2-volumes in the soil;
- charcoal seems to establish alkaline soils which contribute to micro-organism development; increasing the number of micro-organisms in the soil seems to improve fertility of the soil;
- charcoal could act as fertiliser carrier, but in-depth research was not carried out.

Beyond the contributions made by Kishimoto, Suguira [223] and others [224] in 1986 no further developments are known to have taken place to also use charcoal as a soil conditioner.

The work done by LHA Management Consultants [225] in 2003 provided additional data for a forestry and charcoal market subsector analysis. LHA Management Consultants described the total charcoal market and the industry of South Africa as per Figure 4-11.

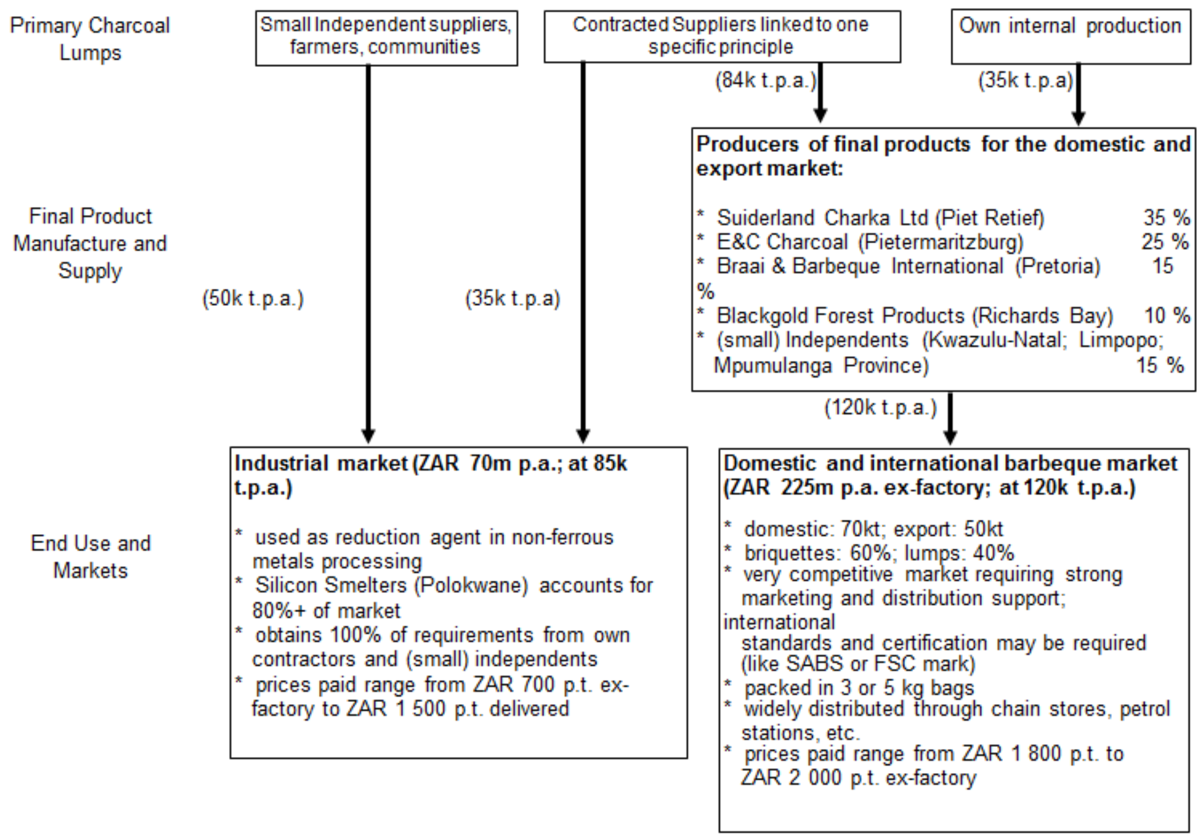

Figure 4-11 South African Charcoal Supply/Demand and Industry Structure [229] in 2003 to 2006

It was found that LHA Management Consultants report [225] provides valuable information, but cross-checking of some facts was considered to be necessary. This was done by collecting additional information during the annual study tours (Table 4-6) to South Africa from 2003 to 2008. Information obtained from interviewees augmented data used in constructing and solving the fast pyrolysis technology model presented in Chapter 8.

The findings from LHA Management Consultants were quoted in other research and projects, notably the 'Assessment of Commercially Exploitable Biomass Resources' [226, 227, 228]; G:ENESIS Reports (Parts I to III):

- 'Part I: The contribution, costs and development opportunities of the Forestry, Timber, Pulp and Paper industries in South Africa' [226];
- 'Part II: Market Analysis' [227]; and
- 'Part III: Technical Notes and Appendices' [228]; and the 'Key issues paper on forestry enterprise development' [229].

It was found that the charcoal and firewood industry of South Africa is very much entwined with that of Namibia. All large South African producers augment their charcoal briquette production systems and sales by Namibian charcoal imports. The Namibian charcoal lumps are said to be too small for repackaging and onward sales. Namibian charcoal is therefore briquetted in South Africa.

As the economies of Namibia and South Africa continue to grow, it is expected that the consumption pattern of wood-based biomass mass will shift from pre-dominantly domestic use as basic energy supply, towards more industrial and recreational use of firewood and charcoal. Further, in South Africa [230] the demand for electricity will grow. A similar trend is expected for Namibia [18]. It is expected that in future the trend to shift consumption away from traditional fuels (wood, dung and bagasse) through transitional fuels (coal, paraffin, LPG) to electricity is likely to continue, based on previous experiences. Electricity allows for more efficient energy use than coal, wood and paraffin, especially for heating water in a domestic setting. Residential energy use is expected to grow at the same rate as the population in South Africa and Namibia at 1.4% and 1.8% respectively per annum [231, 232]. Industrial energy use is expected to follow economic growth trends, on a one-on-one gross domestic product growth basis. Wood for domestic heating, cooking and lighting in rural and semi-urban areas in Namibia and South Africa do not have a market price. The population using fuelwood as their only source of energy expect that the value of the wood is zero when they have to collect it themselves.

The latter reports and papers as discussed in this section provided a key milestone on the feasibility of a number of technologies related to converting wood-based biomass to various products. Testing the feasibility of technologies also includes costs (labour, operational and investment); market dynamics; and standards for products and standardisation of conversion operations. Selective information from these reports was used in modelling fast pyrolysis conversion (Chapter 8).

4.5.1.2 Wood tar and pyroligneous acid produced from slow pyrolysis processes

The very high viscosity of wood tar can supplement fuel oil or diesel in many static applications [64] but have lost their value with the rise of petroleum products [70]. In Namibia, the wood tar was primarily used in boilers and furnaces of hospitals, prisons and school hostels between 1980 and approximately 1993 [191], where after the fuel firing system was switched to fossil fuel oils.

Wood tar can be fractioned into its useful components for producing commodity chemicals. Discussions with the petrochemical industry representatives confirmed the latter [54, 233]. Bio-oil from fast pyrolysis could be an alternative (Chapter 7, 8). As only bioenergy production is the focus of this research, chemicals from bio-oil is not discussed further.

Wood tar can also be used as preservative against termites and fungi. Two grades were tested, i.e. low temperature wood tar and high temperature wood tar [201] with high tar content (and creosote content) from the slow pyrolysis process. It was concluded that there were no apparent differences between wood tar from slow pyrolysis process and creosote from petro-chemical conversion processes in terms of ease of treating wood products against termite and fungal attack. Wood products which are to be considered resistant to fungal and termite attack are to be treated under the standard specification for preservative-treated timber under SABS 1288-1980 [234]. However, the registration process is time consuming, and costly [235; 236]. Patent, marketing and distribution issues within various countries were mentioned to be another noteworthy, but costly challenge [237].

In Namibia, the slow pyrolysis 'wood tar' was successfully sold in bulk to a Namibian supplier of veterinary medicines, instruments and vaccines. The moisture, acetic acid and wood spirit from oils were removed and the resultant wood tar was mixed with an ointment and was sold as a cure to common hoof-illnesses of cattle, sheep, goats, pigs and horses in Namibia and South Africa. This was stopped in 1997 after AGODA Carbon ceased operations in Namibia. Subsequently wood tar is imported from elsewhere and sold on the Namibian and South African market as 'Stockholm Tar'.

Tests [236] on wood tar revealed that the wood tar is not suitable as caulking agent as it contains too much bonded and unbonded water. But the wood tar contains suitable adhesion agents in which case dehydration of the wood tar is unnecessary. Other literature cited [188, 189] confirmed that substitution of phenol in phenol-formaldehyde resins by using the oil obtained (wood tar) by the biomass pyrolysis containing phenolic components is possible.

The pyroligneous acid is mainly used as basis for the production of organic chemicals, and certain acids can be refined to produce pure acids and acetic essences for human consumption. The component of this mixture which is of commercial interest is acetic acid. For example, the registered trademark 'SURIG' is an acetic acid distilled from condensed pyrolysis liquids from the 'Reichert' retort process (owned by PROFAGUS) in Germany. 'SURIG' is commercially available as household detergent or acetic acid essence for food processing.

4.5.2 Assessment relating to market potential in South Africa

As explained earlier, the South African market offers the greatest potential for pyrolysis products in Southern Africa, regardless of whether the products were manufactured in Namibia or in South Africa. South Africa has the necessary legislation in place for bio-based energy uptake, both power and liquid fuel. Due to South Africa's advanced industrial base, bio-based chemicals or chemical components can also be accommodated in that market. In terms of market possibilities South Africa serves as a model with replication to Namibia being a possibility. Exports of products from pyrolysis to Europe and other parts of the world are also possible as both Namibia and South Africa have preferential trade agreements with the European Union in place.

Under South African conditions, the market for products from pyrolysis conversion of biomass is mainly driven by government policy and fiscal (tax and non-tax) incentives and based on bioenergy targets that have been set in 2007 [50, 241]. The South African Government has published policies and directives for the use of biofuels in 2005 [238] and promulgates its "Biofuels Industrial Strategy of the Republic of South Africa" [7] (section 2.5.4.2). Both renewable targets (biofuels and bio-power generation) are to be seen in the light that South Africa wishes to fulfil its international commitments in terms of the Kyoto Protocol and the Johannesburg Declaration [239]. A Designated National Authority (DNA) as proposed by the Kyoto Protocol [53, 240] was established within the Department of Minerals and Energy to cater for projects aiming to qualify to benefit from the Kyoto Protocol's Clean Development Mechanism by setting up cleaner production systems. At the same time, the

South African economy strives to diversify and expand to regional and international markets regarding power and energy supply. Thus market potential for biomass based energy products can play a key role.

However, what lacks in South Africa is how new bioenergy products will enter the market. Figure 4-12 explains the relationship and information flow between players in the market and the market potential on a regional level for bioenergy products.

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Figure 4-12 Approach for a relationship driven model for biofuels market potential in South Africa [50, 241, 242].

To integrate bioenergy products into the energy product mix in South Africa, the principles of the "Black-Box" approach (section 4.4.3) and the roadmap (section 9.9) are suggested. The approach of the UK based National Non-Food Crops Centre (NNFCC) [242, 243] is useful in directing how such latter 'roadmap' could be derived. The NNFCC approach is based on biomass-to-liquids (BTL) process flows and models the market potential of bioenergy. The BTL process flow can also be seen as a biorefinery approach as diagrammatically represented in this research by Figure 2-1 (conceptual framework). The BTL process flow is marked as the route whereby biomass is converted by pyrolysis, bio-oil is gasified into syngas. Syngas then renders the transport fuels, chemicals and hydrogen. Heat and power are co-products of the main process.

In Namibia, bio-based energy targets to be achieved are not available due to a lack of comprehensive policy and/or legislation [58]. However, a strategic action plan to deploy renewable energy (various types) in Namibia was conceptualised in 2008 [18, 244, 245, 246, 247]. The 'roadmap' proposed by this research on how to introduce new bioenergy products to the Namibian market will necessarily include lessons learned from South Africa.

4.6 CONCLUSIONS

Modelling aspects to explain the conceptual framework adopted for this research have considered various relations between national and international drivers on bioenergy with a view to introduce novel thermo-chemical conversion technology, i.e. fast pyrolysis, in Namibia and South Africa. The model to be derived for Namibia aims to link the macro dimension to the micro dimension by incorporating and translating government policy instruments through research and new technology to convert wood-based biomass for the benefit of socio-economic development and growth. In South Africa, the biofuels directive's [7, 238, 248] main aim is social empowerment and deployment of advanced technology, without jeopardising food security. Borsboom *et. al* [249] and Roos [250] support the need for African countries to pro-actively use policy to convert forest and other wood-based resources into sustainable bioenergy for the improvement of social wealth and empowerment. To some extent the South African government has introduced programmes which aim to utilise the vast forest resources of the country for the improvement of socio-economic conditions in that country [152, 158,]. On the one hand, considerable potential for bioenergy in South Africa exists, but would require that the biofuels directive is expanded to also embrace wood-based biomass as a resource for energy (fuel and power) generation through the thermo-chemical conversion route, e.g. fast pyrolysis. On the other hand, Namibia still needs to develop policies which are conducive to the use of bioenergy at national level; and South Africa could lead as example. At a national and international level, Namibia and South Africa subscribe to environmental sustainability. Certain national consents (e.g. licenses, emission regulations, monitoring and control mechanisms) to govern environmental issues associated with the use of novel technologies, like fast pyrolysis to generate bioenergy need to be dealt with in both Namibia and South Africa. Another fundamental issue to be resolved: will the licences to operate a fast pyrolysis plant be provided under the agricultural sector, or rather under the energy sector, or even under the trade and industry sector due to the trading value being added to biomass materials.

In the Namibian case, socio-economic improvement is not yet based on pro-active policies that seek to utilise the vast wood-based biomass resources for bioenergy. Technology deployment is key in this regard. The limited amount of bioenergy produced in Namibia uses at least partly bush, but the technology employed to convert the bush to bioenergy, and in this case charcoal is based on primitive technology.

The models discussed and the literature reviewed in this chapter form the basis for methodology of data analysis and modelling of bioenergy potential derived from fast pyrolysis. Chapters 6, 7, 8 and 9 discuss the aspects mentioned in the conceptual framework (Chapter 2) and the principles underlying scenarios for the models in more detail, bringing together aspects of biomass availability and utilisation with their pyrolysis conversion in an optimised manner. Chapter 5 presents the data required for the respective models. Marketing of the products derived from pyrolysis conversion will also be discussed, bearing in mind policy requirements and market interplay in South Africa, Namibia and Europe, for example (section 4.5). The assumptions used for the models are also presented in the respective chapters and again in a summarised there.

5 DATA AND METHODOLOGY OF DATA ANALYSES

Data on agricultural and related production systems in general is available in Namibia and South Africa. In the Namibian case biomass data is highly dispersed, discontinuous and in many cases raw or aggregated in monetary terms; i.e. for similar data types, data is not published in the same format. Data specifically relating to wood-based biomass is not freely available, and access to private collections were thus also used. By including this chapter in the research, modelling is eased and data is presented in a format which could also be used by others. The structure of the data by-and-large follows model analysis as presented in Chapter 4 and modelling requirements and assumptions (Chapter 6, 8) and desired outputs (Chapter 9).

The methodology applied to establish data requirements, collect and analyse data as well as present data sets in this research is explained throughout the chapter and in relation to the data sets presented, for both Namibia and South Africa. Methodology of data analysis can be summarised according to the following criteria (Chapter 4) and the actual presented data sets, as per below.

- Socio-economic, ecological and national policy indicators
- Link to other sectors and land use indicators
- Spatial indicators
- Dynamic features of data (e.g. existing formulae, stationarity, cointegration)
- Data sources and/or manipulation, if needed and how it was applied.
- Presentation of data sets used in this research

The aforementioned criteria are discussed in greater detail under each data set considered. Consequently, data for wood-based biomass resources, techno-economics, and markets and marketing of products were considered. The analytical data for products from fast pyrolysis were generated through experimental work (Chapter 7) and augmented by literature review (Chapter 4).

5.1 BIOMASS DATA REQUIREMENTS AND AVAILABILITY - NAMIBIA

5.1.1 Socio-economic, ecological and national policy indicators

This research focussed on farmland areas which are more densely populated than 2,500 TE/ha (section 3.4.4; section 3.4.6). In the Namibian case bush encroachment is said to pose challenges on the ecological sustainability [251, 252], productivity of agricultural production systems and their management [253,265]; and has increased substantially and rapidly over the last 50 years; leading to a loss of job opportunities and a total collapse of many farming enterprises [98]. The reasons for bush encroachment have not been investigated in detail. Fast pyrolysis to convert the wood from bush encroachment to generate energy is proposed as sustainable solution to for example curb bush encroachment and/or reclaim productive livestock farming areas.

In addition, the information as presented in section 4.1.1 is relevant, and data on the 'optimal' level of bush coverage is required. However, literature on the socio-economic or ecological impact of bush encroachment and policy statements do not elaborate what the 'optimal' level of bush coverage should be to bring the farming land's carrying capacity back to balance. This research considered the Joubert *et al* [259] proposal that the standing density of bush (in TE-units/ha) for ecological and socio-economic reasons should not exceed the equivalent of the long-term average rainfall (mm/a). Rainfall data is available; the long-term average rainfall for the areas affected by bush encroachment has been established and is presented in Table 5-1. For some farmland areas, this research suggests that the 'optimal' level of bush coverage should not be lowered for ecological and socio-economic reasons; the areas are already prone to desertification [254], and the communities living there-in depend on wood as residential fuel [114]. The 'optimal' level of bush coverage is suggested under section 5.1.3. This research considers that a healthy ecological state of the farmland areas must be maintained; thus a minimum level of bush coverage should be sustained. Therefore, (i) bush coverage (TE-units/ha) should not decrease below the equivalent of the minimum long-term average rainfall (mm/a) (Table 5-1); and (ii) bush coverage (TE-units/ha) for any farmland area according to the principles of Joubert *et al*'s proposal should range between the equivalent long-term average rainfall for that area and threshold of 2,500 and. Any amount above 2,500 would by definition be considered as bush encroached.

Table 5-1 also presents rainfall data of all farmland areas; this is necessary as bush encroachment is likely to spread over time and affect new areas. The latter is explained further under section

5.1.3 below on spatial indicators.

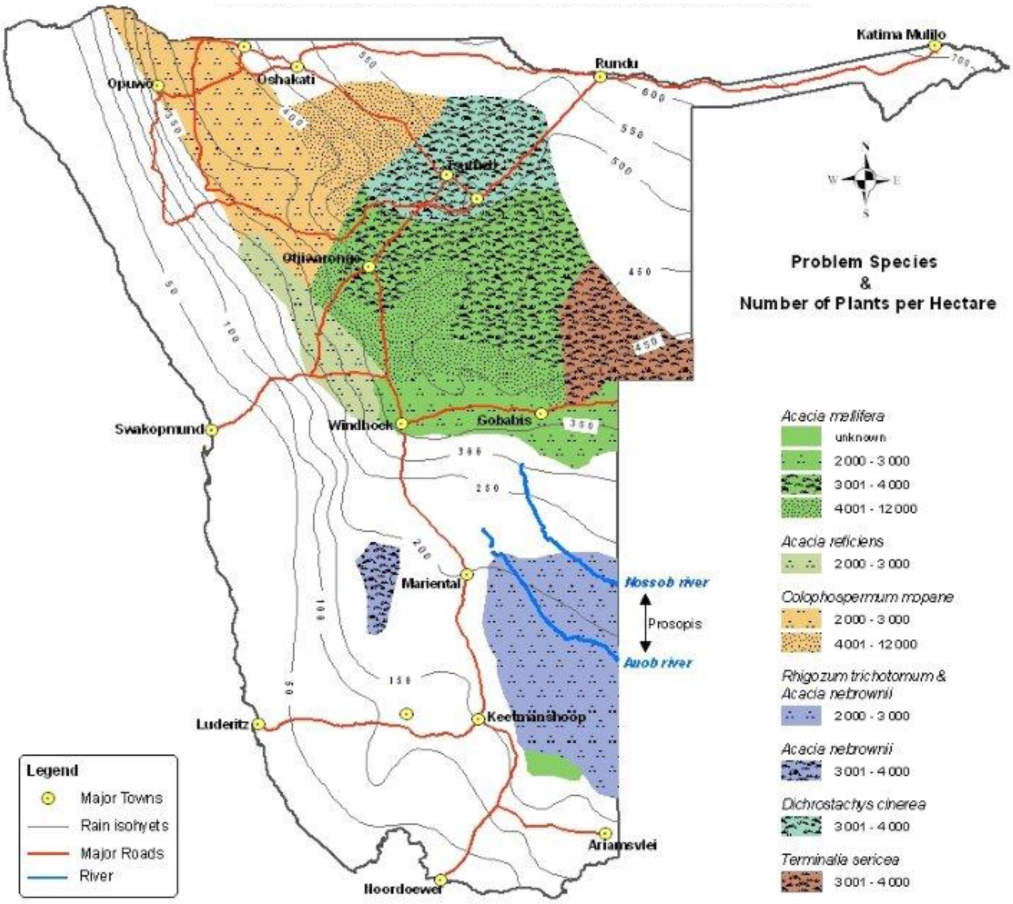

Figure 5-1 Distribution map of bush encroachment in Namibia; highlighting bush encroachment in commercial and communal farmland areas in 2013 and livestock production centres. Based on distribution map of 2004 [254, 255, 256].

Rainfall data is presented assuming the 2013-state of bush encroachment [adapted from 256]. The farmland areas Karasburg, Keetmashoop, Lüderitz, Swakopmund and Walvis Bay are not mentioned in Table 5-1 as they fall into the arid ecological zones of Namibia and are not likely to be prone to bush encroachment. Katima Mulilo falls into the semi-tropical ecological zone of Namibia, where tree species declared as bush encroachers do not currently grow [254], or are not likely to occur in the medium to long term.

Table 5-1 Computed long-term mean annual rainfall of farmland areas affected by bush encroachment in Namibia [data analysed from 83, 86, 89, 257, 258, 259, 260, 261]

Name of livestock production district	Long-term mean annual rainfall (mm/a) [261]	Long-term minimum annual rainfall (mm/a)	Long-term optimal level of bush coverage as per Joubert *et al* [259] (TE-units ha^{-1})	Minimum level of bush coverage (TE-units ha^{-1}) - rounded
Eenhana	509.38	221.00	510	220
Gobabis	338.49	124.25	340	125
Grootfontein	491.64	207.96	490	210
Karibib	220.34	13.30	220	220
Khorixas	281.43	33.75	280	280
Mariental	175.83	34.75	175	175
Okahandja	348.89	114.60	350	115
Okakarara	364.80	153.80	365	155
Omaruru	285.55	42.90	285	285
Ondangwa	458.44	134.30	460	460
Opuwo	144.60	0.00	145	145
Oshakati	431.85	94.93	430	430
Otjinene	407.40	155.40	405	405
Otiwarongo	410.18	152.78	410	155
Outjo	386.92	141.80	385	145
Rehoboth	241.06	35.50	240	240
Rundu	535.06	157.73	535	535
Tsumeb	526.32	222.48	525	225
Tsumkwe	445.46	0.50	445	445
Uutapi	424.58	70.70	425	425
Windhoek	366.39	140.92	365	140

Decreasing bush encroachment levels in Namibia to the ‘optimal’ levels, potentially renders large quantities of wood-based material that could to be converted by fast pyrolysis to produce bioenergy. De Klerk [265] estimated that the harvestable amount of wood-based biomass varies between 8-20 wet-t/ha, and depends on the local vegetation and weather conditions. To estimate how much wood is available to specifically fast pyrolysis, biomass data was required. The latter data is not readily available in Namibia. However, maps which visualise the areas which are bush encroached can be used by following the combined methodology of Bester as explained in de Klerk’s report ‘*Bush encroachment in Namibia*’ [265] and Zimmermann *et al* [262]. Bester derived regression formulae for each type of bush encroachment species as visualised by Figure 5-1. Bester [96] cautioned the use of the regression formulae, as these were a ‘first try’ to derive the weight (in wet kg) of a TE-unit of a certain bush encroachment species. Therefore, 100 TE-unit samples of each bush encroachment species were physically obtained, measured and weighed. The regression formulae as presented by Bester [265] were tested.

Table 5-2 **Average mass (kg) of TE-units of encroacher species based on 100 TE-unit samples, and the theoretical mass of TE-units based on Bester's formulae [96, 265]**

Bush encroachment species	Average Mass (n=100) (kg)	Average diameter (n=100) (mm)	Bester's formulae, based on publication of de Klerk, [256]	Average mass solving Bester's formula (D=15cm)
Acacia mellifera* subsp. *detinens	10.80	114.61	y_{AM} = -10.970+(0.768*D)-(0.0124*D^2)+(0.0000826*D^3)	-1.96
Acacia reficiens	10.80	107.67	y_{AR} =5.093-(0.2567*D)+(0.0059*D^2)+(0.0000116*D^3)	-2.39
Colophospermum mopane	4.74	14.22	y_{CM} = 42.119-(0.0680*D)+(0.00275*D^2)+(0.0000170*D^3)	41.77
Dichrostachys cineria	5.07	101.96	y_{DC} = 115-(0.0680*D)+(0.00275*D^2)+(0.00000888*D^3)	114.63
Termalia sericea	5.77	140.10	y_{TS} = 26.866-(0.609*D)+(0.00463*D^2)+(0.00000572*D^3)	18.79

The reason why the Bester formulae were not used is that applying the standard definition of an TE-unit (diameter between 10 and 15 cm at knee-height) to these for the various species resulted in questionable mass outputs, including e.g negative mass (for *A. mellifera* the 15cm diameter results in a negative mass of 1.96kg). For this reason, it became necessary to collect real data which was done by physically sampling (cutting down, measuring diameter and weighing) 100 TE-specimen and thus determining the average TE-mass for each species. The comparison between the actual wood-base biomass weights and the result that would have been calculated from the sample using Bester's formulae is provided in Table 5-2.

Based on the initial work by Bester [91, 96, 265], Zimmermann and Joubert [262, 265] conducted a desktop study to derive wood volumes per species, expressed in TE-units from Bester's maps. They correctly called their work "a crude quantification" and concluded that "the results of this study need to be treated with a lot of caution". However, to date the work of Zimmermann *et al* [262, 265] is the only one which exists. Hereafter the actual average TE-biomass mass as per 100 TE-samples was used to establish the potential average yield ().The results of the current standing densities and total level of bush encroachment across Namibia in 2013 (based on Figure 5-1) are presented in Table 5-3. These approximate values were required to determine the potential biomass yields and their subsequent sustainable harvest potential and feed-in to the bioenergy model.

It is acknowledged that the values from the TE-samples are crude, but were representative of the various species growth forms and therefore a good enough estimate for the purpose of the modelling exercise. The credibility should not be unduly influenced in terms of sustainable wood-based biomass supply to fast pyrolysis plants.

Table 5-3 Approximate area and distribution of densities covered by different dominant bush encroachment species in freehold and non-freehold land areas (2013)

Category of bush encroachment		Type of Land Area Affected (ha)	
Main bush species	**Bush density (average TE ha^{-1})**	**Freehold land (commercial farmland)**	**Non-freehold land (communal farmland)**
Colophospermum mopane	2,500	266,422	4,933,349
Acacia reficiens	3,000	1,460,752	780,587
Acacia mellifera* subsp. *detinens	2,000	1,192,709	318,218
Colophospermum mopane	4,000	381,381	2,897,218
Acacia mellifera* subsp. *detinens	8,000	1,704,106	51,966
Acacia mellifera* subsp. *detinens	4,000	4,428,387	2,440,137
Dichrostachys cinerea	10,000	2,586,128	1,841,483
Acacia mellifera* subsp. *detinens	5,000	197,720	0
Termalia sericea	8,000	966,490	2,079,706
Rhigozum trichotomum	2,000	899,852	48,590
TOTAL		**14,087,947**	**15,391,333**

The information contained in Table 5-3 is derived from converting map data into exact areas (in ha) affected by bush encroachment in farmland areas, and more specifically livestock district areas using open source software QuantumGIS®. The mapped demarcations of constituencies, farmland and livestock district areas (i.e. the shape files of the maps) which can be imported into spreadsheets used by QuantumGIS® are freely available from the Namibia Statistics Agency [263]. In addition to having quantified the bush encroachment mapped areas (where bush encroachment is expressed as TE-units), the wood-based bush quantities that could be converted by fast pyrolysis to derive bioenergy, as expressed in kg/ha or t/ha. The resultant quantity of wood-based material per type of farmland area and bush encroachment species is presented in Table 5-5. The wood-based material yield assumes that only bush-stem TE-units will be used; not the leaves, twigs, branches or off-cuts of the bush. In estimating the potential for fast pyrolysis conversion before continuing with detailed modelling work (Table 5-5), the potential wet-t wood yields are based on the first time harvest of the bush material as per standing densities in 2013. Subsequent harvesting cycles and their estimated yields were provided for specific areas only (Table 5-4).

For planning purposes bush harvesting and re-growth needs to be established (section 6.1). Such plan would also consider ecological and economic sustainability and it is therefore assumed that a wood yield of approximately 55% of the initial harvest is achieved as from second harvest; and then again a wood yield of 55% of the second harvest is achieved from the third harvest. Aftercare measures are necessary to prevent substantial bush re-growth or re-occurrences of bush encroachment. The sites cleared are assumed to remain ‘un’-encroached for between 15 and 20 years after the last harvesting intervention; the infestation levels would have considerably reduced if all prior harvesting and aftercare interventions were carried out successfully and at the suggested intervals. Even with a medium term harvesting cycle of 20 years, the wood resource was estimated to be sustainable for a period of more than 100 years.

Furthermore, wood-based biomass yield cannot practically be 100% of the bush encroachment levels for the Okakarara and Otjiwarongo farmland districts (Table 5-16). Thus yield is assumed to be 80% at first harvest. Accordingly, wood yield after the first harvest is adjusted too. A harvesting (or other types of clearing) schedule is shown below in Table 5.4 with potential yields of wood-based biomass made available for fast pyrolysis conversion to energy and/or other products.

Table 5-4 Harvesting (or other types of bush clearing) schedule for clearing and/or aftercare and assumed yields from clearing bush encroachment in a socio-economically and ecologically sustainable manner

Harvesting schedule	Year of inter-vention	Bush har-vesting level (%)	Okakarara - biomass yield available for processing (wet-tha^{-1})	Otjiwarongo-biomass yield available for processing (wet-tha^{-1})	Wood yield ratio (%)
1. First harvest	1	95	36.44	48.15	80
2. First follow up harvest	4	55	20.04	26.48	44
3. Second follow up harvest	9	30	5.92	7.82	13
4. First aftercare harvest	19	10	0.46	0.6	1
5. Second aftercare harvest	20	5	0.0	0.0	0

Additional wood-based biomass would be available from subsequent harvesting cycles making the resource sustainable over a long term. However, TE-unit samples of the various species from such previously harvested sites were not available to this research. For modelling purposes, it was assumed that the yield drops with each harvest according to the harvesting schedule in above Table 5-4.

Table 5-5 Approximate wood yield from different dominant bush encroachment species in freehold and non-freehold land areas; wood yield is based on wet-weight of the same species in the same farmland area after first time harvest (2013) [adapted from 262, 265]

Category of bush encroachment		Average mass (kg/TE-unit)	Total potential yield from type of land area affected (t)		
Main bush species	Bush density (average TE ha^{-1}) [262]		Potential yield (wet-t ha^{-1})	Potential yield from freehold land (commercial farmland) (Mt)	Potential yield from non-freehold land (communal farmland) (Mt)
Colophospermum mopane	2,500	4.74	11.85	3.16	58.46
Acacia reficiens	3,000	10.80	32.40	47.33	25.29
Acacia mellifera* subsp. *detinens	2,000	10.80	21.61	25.86	6.88
Colophospermum mopane	4,000	4.74	18.96	7.23	54.93
Acacia mellifera* subsp. *detinens	8,000	10.80	86.43	147.29	4.49
Acacia mellifera* subsp. *detinens	4,000	10.80	43.22	191.37	105.45
Dichrostachys cinerea	10,000	5.07	50.69	131.09	93.34
Acacia mellifera* subsp. *detinens	5,000	10.80	54.02	10.68	0
Termalia sericea	8,000	5.77	46.14	44.60	95.96
Rhigozum trichotomum	2,000	Not sampled; it was assumed that this resource has no commercial value [265]			
TOTAL				**608.60**	**444.80**

5.1.2 Link to other sectors and land use issues

For this research land ownership in terms of agricultural production systems is of importance as it guides in which manner access to the wood-based raw materials is to be obtained and how it can be utilised as resource for conversion via fast pyrolysis. The wood-based biomass and other natural resources belong to the land owners, except in municipal or proclaimed or protected areas where there is mixed ownership and/or regulated use of natural resources. Similarly, the right to use water in processes or production systems is determined by land ownership and national natural resource management regulations [77, 78]. Wood-based biomass from bush encroachment is available from land which is also used for agricultural production systems and national parks. Land ownership in the agricultural sector is divided into freehold (commercial farm) [77] and non-freehold (communal farm) [78] land. Data on land ownership is readily available from official information sources like the Deeds Office of the Namibian Ministry of Lands Reform, and the Namibia Statistics Agency. Some 31Mha of farmland is demarcated as freehold land; and some 52Mha of farmland is demarcated as non-freehold land. The non-freehold land includes nationally protected (e.g. national parks) and communal land areas. Communal land includes both communal farmland and unproclaimed residential, but remote/rural areas. The freehold land includes proclaimed and municipal land areas. The data set on land ownership required for this research to which extent bush encroachment occurs is presented in Table 5-3.

The actual size of demarcated agricultural land is important in the context of potential bush encroachment spread over time (section 5.1.3). Land demarcated for agricultural production (crop and livestock farming; freehold (commercial) and non-freehold (communal) land evolved over time. The demarcations were legislated first under the Union of South Africa, then under the Administration for Southwest Africa, i.e. Republic of South Africa. Farmland demarcations were not changed under the Republic of Namibia since 1970 (Table 5-6).

Table 5-6 Changes in agricultural land size from 1930 to 2011

Period	Area demarcated as agricultural land (freehold and non-freehold land; Mha)
1930 – 1947	14.82
1948 – 1969	36.16
1970 – to date	65.41 (of which 51.72Mha is dedicated to livestock farming only)

Access to the wood-based biomass, e.g. harvesting of bush in freehold (commercial) farmland is obtained through direct negotiations with the land owner. Access to the wood-based biomass in non-freehold (communal farmland or national parks) can only be obtained through either; participation in public procurement processes (open or invited tenders); approaching and negotiating with communal land boards, or forming partnerships with traditional, regional, or local authorities thereby obtaining land use rights (e.g. a permission to occupy (PPO) or 99-year leasehold). The benefit of a project carried out on communal land must clearly spell out the national or public interest, and profits should be shared with the community to whom such land is assigned. Central government authorisations may also be required.

5.1.3 Spatial indicators of bush encroachment

In view of techno-economic viability of a fast pyrolysis conversion plant it is important to sustain a high supply of raw material and as cost efficiently as possible over a prolonged period. With the area demarcated as farmland (Table 5-6) it can be established how significant (or insignificant) the development of bush encroachment is in terms of the agricultural production process and sustainability of a fast pyrolysis conversion plant in the same area. That is, what is the total identified area of bush encroachment relative to the overall farming area; and how the bush encroachment area expands or reduces over time. Bush encroachment area expansion/reduction is discussed below.

The *Bush Encroachment in Namibia* Report of 2004 [265], estimated that some 10Mha were infested with encroachment bush in 1970, while this figure is said to have increased to 26Mha by 2004 [98, 265], and some 30Mha by 2013 (Table 5-3). Densities of bush encroachment in commercial and communal farmland areas vary widely, with an average, one-off yield of between 5 and 24 t/ha measured as equivalent TE-units, and depending on the type of species, geographic and climatic region and soil condition in a specific area [254, 262, 264, 265, 259]. The weighted average bush population spread rate for the period 1957 to 2013 was estimated at 4.35%; details are presented in Table 5-3.

Table 5-7 Reported bush encroachment developments

Researcher and/ or report, and year of report	Bush encroachment (wet-Mt total)	Bush encroachment (Mha total)	Time and land type (year) when & where	Total area increment between two following periods (%)
Rawlinson, J. Meat Industry of Namibia 1893 – 1993. 1994 [89]		4.56	1957 commercial farmland	
De Klerk, J N. Bush Encroachment in Namibia. 2004. [265]		10.00	1970 commercial farmland	119
Reports compiled in 1985 and 1986 present different figures for bush encroachment, e.g. Lubbe and Slater, 1985 present the total bush encroachment potential to be 100 Mt; presented at Conference "Bush Encroachment and Control in Perspective", presented by the Rietfontein Farmers Association and the Grassland Society of Southern Africa, 21 & 22 April 1993, contribution by Mr Chris Shikaputo, Chief Forester, Directorate of Forestry, Ministry of Agriculture, Water & Rural Development, titled "Bush Encroachment in Namibia - an environmental and forestry perspective".	100	estimated 3.38	1985 commercial farmland	-66.16
Rawlinson, J. Meat Industry of Namibia 1893 – 1993. 1994 [89] presented data as total area of bush encroachment for 1986.		14.43	1986 commercial farmland	326.41
De Klerk, J N. Bush Encroachment in Namibia. 2004. [265]		17.80	1991 commercial farmland	23.37
De Klerk, J N. Bush Encroachment in Namibia. 2004 265(based on work of Bester [266])		24.19	1996 and 2002 Commercial & communal farmland	26.41
Zimmermann *et al*. 2002. [262]		26.26	2002 Commercial & communal farmland	7.88
Table 5-3 as analysed using QuantumGIS®		29.48	2013 Commercial & communal farmland	12.26

The weighted average annual bush population growth rate of 4.35% from Table 5-7 was computed excluding the outlying growth rate as reported for 1985. The data for 1985 was omitted as it is practically impossible to decrease bush by over 60% over a 15 year period, and within just one year to increase it by over 300% again; neither did specific events or climatic occurrences as reported over the same period allude to such (Table 5-8). It is acknowledged that basing bush population growth on area spread only may not be a true reflection of the bush growth. However, this is the only published data available, and was thus assumed to be representative for bush growth at national level.

Furthermore, it was accepted that various events have influenced bush population growth as outlined by farmer interviews (Table 4-1). Regardless, these reported events (climatic, political or management) do not seem to have limited spread of bush over the period 1897 to 2013.

It is acknowledged that this is not the case in reality as soil types, climate, topography, precipitation would differ from district to district and from area to area within a district. However, for a lack of other data pertaining to the respective district areas, the national bush population growth rate was also applied to all the various districts.

Table 5-8 Events which impacted on agricultural production in South West Africa (1897 – 1989) and Namibia (1990-2013) which may have had an impact on bush population growth rates [89, 267, 268]

Event(s) in a certain period	Time frame	Primary effect as reported	Secondary effect	Remedial or other action taken by authorities
Lack of Surface Water	1897 - 1935	limited livestock numbers	overgrazing on 1/3 of settled areas, while 2/3 is under utilised	sinking of boreholes; wells by administration; after 1935, allotment of "own" land; Land Settlement Ordinance of 1920
Economic Recession; Great Depression	1920-1930s; 1940s	cancellation of farm allotments; surrender after World War I; recovery of rangeland conditions	>50% reduction in stock numbers; lack of internal markets; problematic logistics situation	resettlement of farmers from SWA to SA union; prices for cattle were more favourable in SA, and better assistance to farmers there;
Drought	1920 - 1923; 1933	dieback of flora		
Cattle Improvement Ordinance of 1930	1930	switch from meat to dairy industry; import of improved livestock stud quality to boost dairy industry; fencing off of allotments		Cattle:= mainly dual purpose breeds which are draught resistant, deliver a lot of milk and can be used for beef production, thus e.g. Afrikaner (hardy and good beef characteristics); small stock:= multiple purpose meat, pelts, wool, milk.
Favourable rain conditions	1934 - 1939	increased livestock numbers; better farming output; re-growth of flora	excellent export market conditions (e.g. Karakul) Total cattle number- 1003100; total small stock number-4928600	
Drought	1941	dieback of fauna & flora		
Above average rainfall	1942	recovery for fauna & flora but army worm plague destroys large rangeland areas		
Drought	1944 - 1947	moving of cattle from south & central areas to north Namibia; Karakul moved to Northern Cape for emergency grazing	decrease of overall stock numbers by some 32%	
Drought	1947 - 1949	unabated drought in southern Namibia	dieback of fauna and flora	
Above average rainfall	1950	recovery of livestock numbers by some 31%		

Event(s) in a certain period	Time frame	Primary effect as reported	Secondary effect	Remedial or other action taken by authorities
Low animal husbandry & its administration	as from early 1949 to 1960s; proper farm planning and management commenced, but only as from 1953 with the full implementation of cattle ordinance	low output; no supportive farm administration *"cattle farming in Namibia was very primitive and came closer to robber-farming than rotational utilisation of natural resources"* [263]	ecological detriments; farms too small to render sufficient income; 50% in south and 70% in north; vigorous growth of flora	long term agricultural policy commission = conservation/reclamation of soil& pastures, water & augmentation of existing supplies; adopt improved farming practices to improve quality/quantity of farm products; farming with goats which belonged to natives was disallowed by policy due to detrimental effect on environment 90% of all farms were planned/established before end 1960s with number of camps at least doubling from mid 1940s level
Focus on dairy ranching	1953 - 1958	intense extensive dairy farming	drainage of biological capital; eventual collapse of extensive dairy farming	
Drought & FMD	1959 - 1962	continuous decline in cattle numbers followed by a period of over burdening grazing to compensate losses	disturbed ecological balance; increase in bush encroachment due to continuous removal of grass and herb layer thus removing competition; absence of veld fires to kill bush seedlings; reduced no of browsing animals; climatic & other conditions which favour woody vegetation	Soil Conservation Act No. 76 of 1969; however, not one farmer was charged when found trespassing the law
Introduction of commercial game farming with aim of preserving wildlife diversity	1967	commercialisation of game farming	restocking of farms with divers sorts of game; more browse of especially bush & shrubs no proper research was done to properly stock, harvest and market game	economising farming where game farming was considered a source of income and not nuisance
Intermittent drought	1970 - 1973	continuous decline in cattle numbers		Nature Conservation Ordinance No 4 of 1975 = regulates game harvesting and protection of certain game species
Intermittent drought	1979 - 1983	continuous decline in cattle numbers	reduction in overall flora for livestock farming	Land Reclamation Strategy 1988, Administration for Whites
Specification of economic farming	1983	number of commercial livestock confined to a farming unit is confined; expected		1 LSU=500kg (adult cow, bull, or calf) 1 LSU = 6 SSU (adult goat, sheep)

Event(s) in a certain period	Time frame	Primary effect as reported	Secondary effect	Remedial or other action taken by authorities
unit		better rangeland management and prevention of over-grazing		carrying capacity is # ha of land required to feed 1 LSU for 1 year
Northern Communal Areas (NCA) – severe drought	1983	decrease of cattle numbers from 110000 to 15000 bush is 'attacked' by a fungi; large scale dieback of especially *A. mellifera*	dieback of flora too due to drought	
International market for Karakul sheep skins collapses	1985 - 1990	Karakul sheep numbers reduce from 5million to some 300k overtime, especially in southern Namibia	browse of shrubs and bush reduces tremendously; bush can spread faster	
Commencement of conservancies for wildlife	1993	proper game management (e.g., seeing game as an additional source of income)	leads to return of more indigenous, endemic and exotic game on otherwise agricultural land for livestock/crop production only; game numbers increase considerably, confined to conservancy areas; initially this reduces bush, later more pressure is put on rangeland to accommodate increased fauna	this seems to be a remedial action, trying to reintroduce game as a means to browse vegetation other than grass (seasonal and perennial); game counts are done only on farms members to a specific conservancy; additional game counts are done by government (Min of Environment & Tourism) for endemic, endangered species (e.g. Hartmann Mountain Zebra)
Intermittent drought	1995 – 1998	decrease of livestock numbers in general	dieback of flora	Government introduces drought relief scheme
Promulgation and commencement of agricultural (commercial) land reform act	1995	Government is enabled to enforce "willing buyer-willing seller" principle, and has first right of refusal to buy agricultural (commercial) land; per hectare land price increases	hasted sales of agricultural (commercial) land; overall livestock production decreases; previously productive farms go out of production, with little to no rangeland management taking place on such farms; some 5Mha is affected	Government resettles previously disadvantaged population groups to farms bought under the "land reform and resettlement programme" Government makes subsidised loans available to resettled farmers under the programme "affirmative action loan scheme"

Event(s) in a certain period	Time frame	Primary effect as reported	Secondary effect	Remedial or other action taken by authorities
Introduction of communal agricultural land reform act	2002	regulating the use of grazing, water points and holding of traditional leasehold in communal land areas	overstocking of livestock in certain areas, especially in the NCA; additional pressure is exerted on rangelands in NCA	
large scale veld fires	2003 – 2006 2006	fires created loss of grazing over some 5Mha in especially large livestock farming areas during these years 2006 very good rains spur off vigorous re-growth of flora	hasted sales of cattle production also bush dieback due to large scale fires	Government introduces a relief scheme, especially in communal farmland areas; additional slaughtering of cattle at export accredited abattoirs
Amendments to Customs & Excise Act 1998	2003	additional pressure on grazing as large numbers of livestock remained in the country as Namibian market gets over-saturated	over time, commercial livestock numbers reduce to accommodate market forces	Notice on introduction of export levies on cattle weaner & pickled skin exports
Amendments to Customs & Excise Act 1998	2007	additional pressure on grazing as sheep remained in the country as Namibian abattoirs were unable to accommodate additional animals to slaughter	over time, fat tail sheep numbers reduce to accommodate market forces	Notice on regulating export of fat tail sheep; 6 sheep must be slaughtered in Namibia, before 1 can be exported live for slaughter in SA
Above average rainfall	2008 - 2012	vigorous re-growth of flora	restocking of commercial livestock, in some areas far more than considered good under recommended rangeland management practice	
Drought	2013	dieback of flora	hasty sale of commercial livestock; dieback of wildlife, especially that confined to conservancy areas where it cannot migrate naturally	Government introduces a relief scheme; additional slaughtering of cattle at export accredited abattoirs, and ‘opening’ of the border to allow additional export of life livestock to South Africa

In addition to reports as summarised in Table 5-7, data on bush encroachment and the possible bush yield in the non-freehold areas were documented in the Ministry of Environment of Tourism forest inventory reports from 1998 to 2003. From the reports, total bush inventory which can be utilised in various ways is as high as 24wet-t/ha [269]. The high yields are partly due to the subtropical ecological zones in north-eastern Namibia [270, 271, 272, 273, 274, 275] which are strictly speaking not bush-encroached (Figure 5-1). In other areas there are almost no trees or the area is declared as arid [276, 277, 278]. The most common bush and tree yield after first assessments was documented as being between 13 and 16 t/ha and consisting mainly of *Acacia*-species [279, 280]; however Table 5-5 indicates that yields above 16 t/ha are possible in very densely populated encroachment bush areas. Table 5-9 presents disaggregated data analysed by this research and according to farmland district centres (similar to rainfall data analyses) as per standing wood densities in 2013.

Table 5-9 Analysed bush encroachment levels of affected farmland areas in 2013

Name of livestock production district	Weighted mean bush density of all species and the bush encroached area (TE ha^{-1})	Total district area affected by bush encroachment (rounded Mha)	District area (rounded Mha)	Total potential yield from all species (rounded wet-Mt ha^{-1})	Type of land ownership bush encroached
Eenhana	4,778	0.6	2	14.02	non-freehold
Gobabis	4,407	3.4	4.8	125.45	freehold & non-freehold
Grootfontein	9,162	2.4	2.4	106.79	freehold
Karibib	3,000	0.6	1.5	18.59	freehold
Khorixas	2,672	2.3	5.5	42.77	non-freehold
Mariental	2,000	0.9	10	3.6	freehold & non-freehold
Okahandja	3,912	0.5	0.6	20.41	freehold
Okakarara	4,232	1.4	1.4	65.83	non-freehold
Omaruru	3,241	0.8	0.8	29.53	freehold
Ondangwa	4,000	0.1	0.2	1.39	non-freehold
Opuwo	2,501	1.8	6.8	21.89	non-freehold
Oshakati	Bush encroachment noticeable in some parts		0.2		non-freehold
Otjinene	6,422	1.6	1.7	74.09	non-freehold
Otiwarongo	5,467	3.2	3.2	192.03	freehold
Outjo	3,845	0.7	0.8	20.30	freehold
Rehoboth	2,000	0.05	1.2	0.2	non-freehold
Rundu	10,000	0.7	4.2	33.18	non-freehold
Tsumeb	6,289	4.1	3.2	125.99	freehold & non-freehold
Tsumkwe	2,708	1.7	4.7	79.35	non-freehold
Uutapi	1,394	1.5	2.7	17.59	non-freehold
Windhoek	256	0.9	3.7	30.60	freehold

Bush density (in TE-units) levels per farmland district changed for the period 2002 to 2013; and, bush encroachment spread to adjacent areas over the same period as visualised by Figure 5-1. Table 5-10 provides an indication on how bush encroachment developed over time in the livestock farming areas between 2002 and 2013. The latter time period is highlighted as detailed information is available as presented by Table 5-10.

Table 5-10 Bush encroachment development in farmland areas between 2002 and 2013

Period of assessment	Total district area (Mha)	Total district area affected by bush encroachment (rounded Mha)	Weighted mean bush encroachment level (TE ha^{-1})	Type of land ownership bush encroached
2002, reported in 2004 [265]	32.5	10.5	5,027	non-freehold
	30.2	15.8	5,018	freehold
2013	32.5	15.4	2,222	non-freehold
	30.2	14.1	2,541	freehold

From Table 5-10 it seems that the weighted average bush encroachment level for the Okakarara and Otjiwarongo district has halved. However, bush encroachment seems to spread first spatially before it increases in wood density. The latter is supported by literature which reported on bush encroachment spread, not density levels (Table 5-7).

Apart from considering the selection criteria for wood harvesting, and subsequent bioenergy production via fast pyrolysis such as infrastructure, logistics, handling, storage, manufacturing capability, and costs to harvest bush, it was worthwhile to consider the data as presented in Table 5-9 and Table 5-10 in a graphic manner as per Figure 5-2 and Figure 5-3.

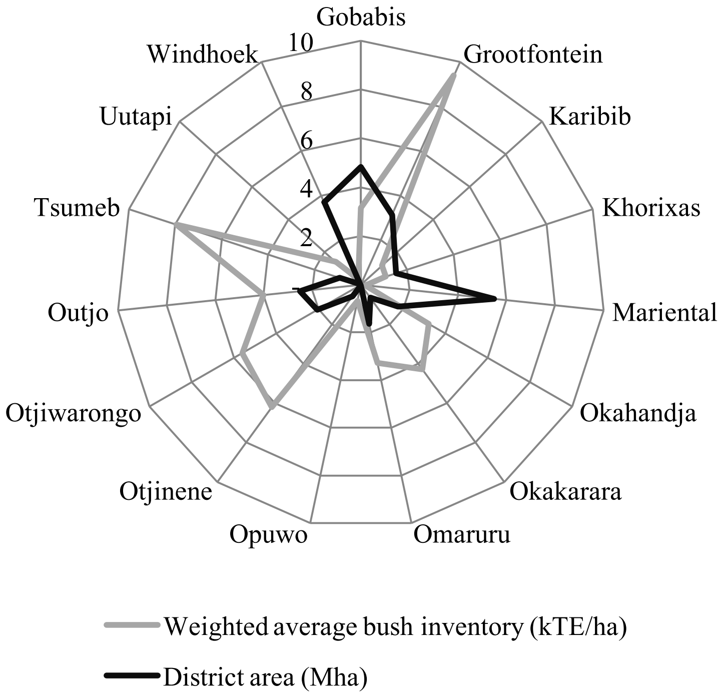

Figure 5-2 Weighted average bush inventory (in kTE ha^{-1}) compared to the size of the commensurate livestock production district in Namibia in 2013

From Figure 5-2 it seemed that harvesting bush material as feedstock for fast pyrolysis conversion would be worthwhile to pursue, if sourced from the livestock production districts of Grootfontein, Okakarara, Omaruru, Otjinene, Otjiwarongo, Outjo and Tsumeb. The standing density of bush, or wood material (in TE-units/ha), is relatively high if compared to the land size.

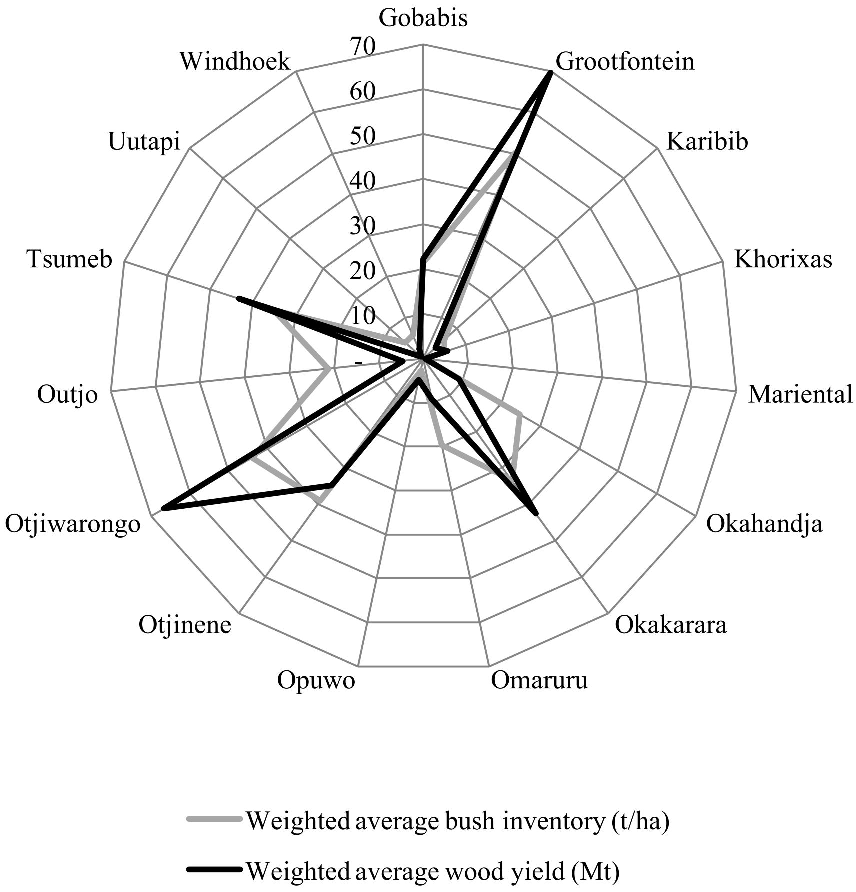

Figure 5-3 Weighted bush inventory (standing density, wet-t ha^{-1}) and weighted average wood yield (in wet Mt) of all livestock production districts which are bush encroached in Namibia, 2013

As mentioned in sections 3.4.4 and 3.4.6, the level of bush encroachment is directly, but inversely correlated to the same farmland's carrying capacity. Table 5-11 presents the carrying capacity developments for the affected farmland areas for the period 1970 to 2010. The Namibia Agricultural Union [98] suggests that commercial livestock production (expressed as stocking rates in kg/ha) should be at least one-third of or equal to carrying capacity (kg/ha), but should not exceed the carrying capacity due to ecological and environmental reasons, to be economically viable for the farmer.

Table 5-11 Agricultural Land's Carrying Capacity vs Stocking Rates from 1970s to 2010 [86, 89, 281]

OVERALL TOTALS						
		1970s	1989 - 2002		2003 - 2010	
AGRICULTURE DISTRICT (Farmland area)	**Total Area of District as assessed in 2003 – ha (rounded)**	**Total Carrying capacity - assessed kg body mass per ha**	**Total Carrying capacity - assessed kg body mass per ha**	**Total Stocking Rate - produced kg body mass per ha**	**Total Carrying capacity - assessed kg body mass per ha**	**Total Stocking Rate - produced kg body mass per ha**
Eenhana	1,070,300			41.64		43.58
Gobabis	4,828,995	37.08	24.98	24.08	25.55	17.39
Grootfontein	3,134,433	44.01	17.43	25.13	17.84	21.40
Karibib	1,886,300	19.30	6.38	4.91	6.41	4.41
Khorixas	1,505,012	18.14	7.90	9.41	8.25	9.71
Mariental	5,494,933	16.71	13.44	9.80	13.39	11.78
Okahandja	1,769,864	36.55	20.11	26.70	20.72	23.52
Okakarara	660,919	45.00	28.57	59.18	28.57	43.88
Omaruru	1,636,375	27.29	13.61	13.04	14.34	13.26
Ondangwa	5,324	36.00	15.00	6,174.86	15.00	2,690.78
Opuwo	24,996	36.00	20.00	2,619.09	20.00	2,828.90
Oshakati	10,235	45.00	15.00	0.00	15.00	0.00
Otjinene	588,721	45.00	30.00	61.81	30.00	63.97
Otjiwarongo	2,052,268	42.24	20.02	14.03	23.04	11.49
Outjo	2,504,822	31.64	14.22	14.05	16.64	12.05
Rehoboth	1,206,108	18.32	11.39	15.59	11.39	11.17
Rundu	299,356	45.00	30.00	146.39	18.52	141.31
Tsumeb	924,331	42.31	18.22	24.81	16.32	94.68
Tsumkwe	1,320,000			3.34		4.66
Uutapi	24,995	36.00	20.00	69.62	20.00	3,826.31
Windhoek	3,701,119	30.98	16.19	17.04	17.51	12.16

Considering the results as presented in Figure 5-2 and Figure 5-3 in combination, it seems that harvesting wood material from Grootfontein, Okakarara, Otjiwarongo and Tsumeb livestock production districts would render the most economic for fast pyrolysis route to follow. However, from Table 5-11 the Grootfontein and Tsumeb farmland areas seem to be already stocked in excess of the suggested carrying capacity. The farmland areas of Okakarara and Otjiwarongo were investigated further; stocking rate with commercial livestock is less than carrying capacity.

5.1.4 Dynamic features of the data

Keeping record of annual bush growth and inventory would assist interested parties in integrating e.g. bioenergy production inputs and livestock production into one system, thereby not perceiving bush as an 'enemy', but a valuable resource to be sustained. In constructing data management records, the rainfall data features are of relevance (Table 5-12).

Testing rainfall data of farmland areas affected by bush encroachment for stationarity is done by conducting the Augmented Dickey-Fuller (ADF) test; the NULL hypothesis is that total annual rainfall data has a unit root. If the unit root can be rejected, the data is stationary. To reject the unit root, the t-statistic value of the variable at 1%, 5% and 10% confidence levels for the number of observations in each respective sample needs to be greater than the critical t-statistic value. The tests are solved in EViews®8. Results are shown for all livestock production districts which are bush encroached, although not all data sets will be used for modelling. Data sets to be utilised for modelling are selected according to the criteria as mentioned in section 5.1.3 above and presented in Table 5-14.

Table 5-12 Data analyses and results rainfall data from the period 1891 - 2012

Data type analysed	Data test conducted	Test result	Conclusions & Remarks
Long term average rainfall of all districts	ADF (unit root test)	t-stat critical value at 1% confidence level v's t-stat result: **-3.48 > -11.40 for 122** observations after adjustments	Reject that long term average rainfall has unit root; therefore data series is **stationary, at 1% level**
Long term average rainfall of **Eenhana**	ADF (unit root test)	**-3.62 > -4.71 for 37** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Gobabis**	ADF (unit root test)	**-3.49 > -10.75 for 102** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Grootfontein**	ADF (unit root test)	**-3.49 > -12.22 for 107** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Karibib**	ADF (unit root test)	**-3.49 > -10.51 for 110** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Khorixas**	ADF (unit root test)	**-3.52 > -9.98 for 77** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Mariental**	ADF (unit root test)	**-3.49 > -10.45 for 105** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Okahandja**	ADF (unit root test)	**-3.49 > -11.78 for 115** observations after adjustments	Data series is **stationary, at 1% level**

Data type analysed	Data test conducted	Test result	Conclusions & Remarks
Long term average rainfall of **Okakarara**	ADF (unit root test)	**-3.54 > -7.79 for 62** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Omaruru**	ADF (unit root test)	**-3.50 > -9.89 for 105** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Ondangwa**	ADF (unit root test)	**-3.50 > -10.35 for 94** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Opuwo**	ADF (unit root test)	**-3.59 > -2.69 for 63** observations after adjustments	Data series is **stationary, at 10% level only.** Data series is very discontinuous
Long term average rainfall of **Oshakati**	ADF (unit root test)	**-3.53 > -6.93 for 67** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Otjinene**	ADF (unit root test)	**-3.50 > -9.59 for 86** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Otiwarongo**	ADF (unit root test)	**-3.50 > -11.57 for 102** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Outjo**	ADF (unit root test)	**-3.50 > -11.22 for 105** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Rehoboth**	ADF (unit root test)	**-3.50 > -10.09 for 110** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Rundu**	ADF (unit root test)	**-3.50 > -9.27 for 99** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Tsumeb**	ADF (unit root test)	**-3.50 > -11.62 for 101** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Tsumkwe**	ADF (unit root test)	**-2.61 < -1.99 for 38** observations after adjustments	Data series is **NOT stationary, even at 10% level only.** Data series is very discontinuous, and too few observations
Long term average rainfall of **Uutapi**	ADF (unit root test)	**-3.51 > -7.56 for 82** observations after adjustments	Data series is **stationary, at 1% level**
Long term average rainfall of **Windhoek**	ADF (unit root test)	**-3.49 > -11.75 for 120** observations after adjustments	Data series is **stationary, at 1% level**

From Table 5-12, all annual rainfall data series of livestock production districts, except that of Opuwo, are stationary. Therefore, using rainfall data in modelling bush growth is eased, as no further data manipulation is necessary. However, rainfall is highly variable, as visualised by Figure 5-4 and Figure 5-5. From Figure 5-5 it can be observed that rainfall is concentrated in the period October to April which falls into the summer season of Namibia.

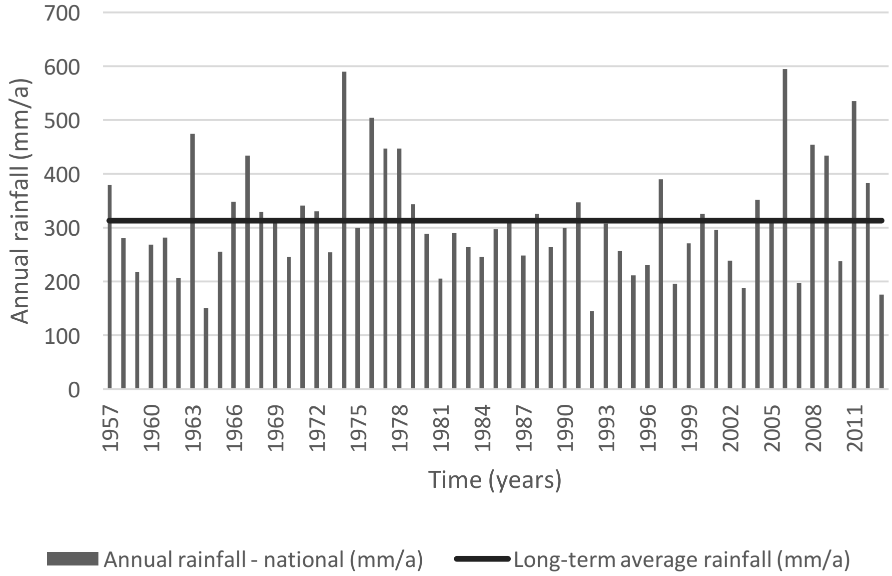

Figure 5-4 Weighted average rainfall of all livestock production districts and weighted long term average rainfall for Namibia, 1891 – 2012 (as per data analyses done using [261])

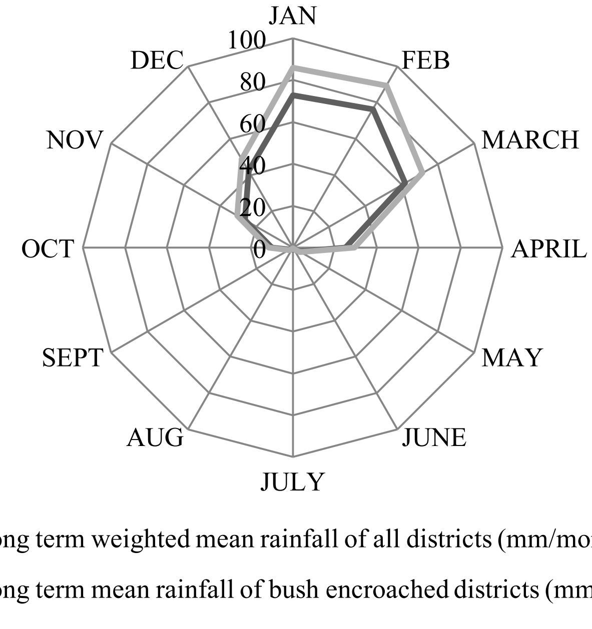

Figure 5-5 Analyses of monthly rainfall of all livestock production districts compared to monthly rainfall of bush encroached livestock districts for Namibia, 1891 – 2012 (as per data analyses done using [261])

From Figure 5-5 it can be deduced that bush encroached farmland areas received more rain on average than the combined farmland areas. The average higher rainfall seems to be one reason why bush (and other plant) growth is more vigorous in certain farmland areas than others. It is not the aim of this research to explain how much bush growth will take place during each season, but rather to find a plausible bush growth (and re-growth) rate to establish the amount of wood from the selected livestock production districts that could be available for bioenergy production on a sustainable basis. Therefore, combining the information of Figure 5-3 and Figure 5-5 provides a strong basis for biomass modelling in the areas Grootfontein, Okakarara, Otjiwarongo and Tsumeb. The analyses results are shown in Figure 5-6.

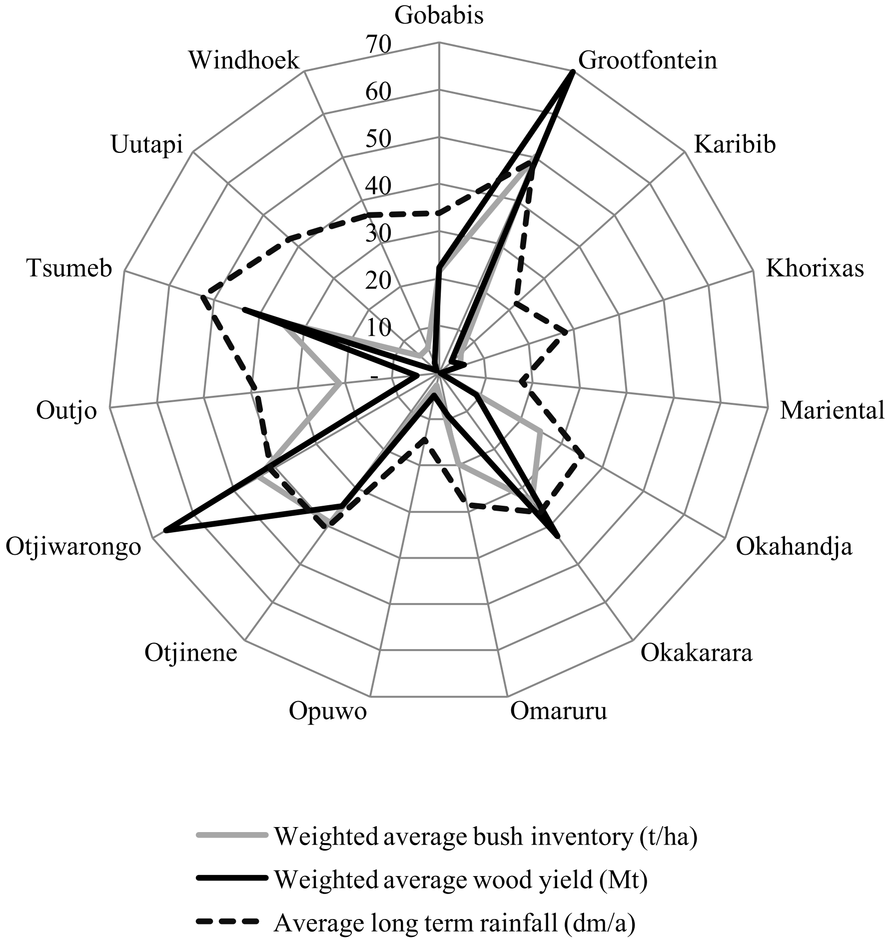

Figure 5-6 Analyses of long term average rainfall (in dm year^{-1}) for the period 1891 - 2012, weighted average standing bush density (in wet-t ha^{-1}) in 2013 and potential weighted average bush yield after first harvest (in wet-Mt) in 2013 of bush encroached livestock districts for Namibia

To measure the impact of harvesting bush material in a certain area in view of improving agricultural land productivity, this research considers total livestock numbers that can be kept (section 3.4.7.1). Scientifically, it would be better to measure rangeland improvements instead of possible additional number of livestock. However, grass or plant biomass other than harvested, and sold wood from bush, do not have a monetary value; and to measure rangeland improvements, scientific research would have to be carried out over several rainy seasons. As a secondary outcome to harvesting bush for bioenergy production, this research sought to establish how decreased bush encroachment could improve livestock productivity. Figure 5-7 presents information on the possible yield of wood (in wet-Mt) after a first harvest, rainfall and current average level of commercially valuable livestock density (in Mt live body mass).

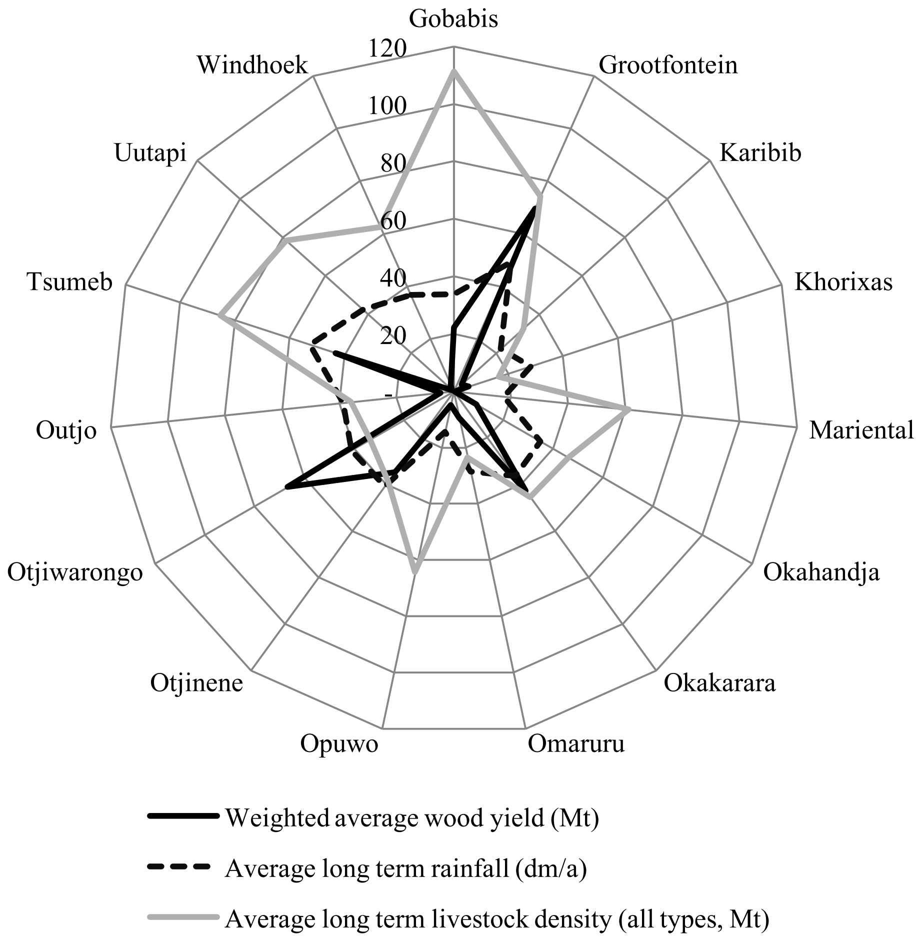

Figure 5-7 Analyses of long term average rainfall (in dm year^{-1}) for the period 1891 - 2012, potential weighted average bush yield after first harvest (in wet-Mt) in 2013, and long term average livestock density of all commercially valuable livestock types (in total Mt) for the period 1986 - 2012 of bush encroached livestock districts for Namibia

From the information presented in Figure 5-7 this research focussed on the farmland areas Okakarara and Otjiwarongo, for the following reasons:

- Wood yield from harvesting bush is considered to be economically viable;
- Livestock density is significantly lower than many other bush encroached farmland areas, therefore bush thinning is considered to be necessary, to improve farmland productivity and livestock output.

- For both areas, the complete farmland area is covered by bush encroachment (Figure 5-1, Figure 5-8).
- Okakarara and Otjiwarongo farmland areas are adjacent to each other, which eases logistics.
- Okakarara and Otjiwarongo farmland areas are predominantly encroached by *Acacia mellifera* spp. *detines*, which eases considerations on techno-economics as these species were tested with regard to thermo-chemical conversion (Chapter 7, section 7.1.1.).
- An electrical distribution hub is situated in the Otjiwarongo district, close to Otjiwarongo town which eases potential power transmission and distribution (Figure 5-10).

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Figure 5-8 Map indicating the constituencies of Namibia; the farmland areas Okakarara and Otjiwarongo are shaded; the livestock prodution area Otjiwarongo is the combined constituency area of 'Otjiwarongo' and 'Omatako'

Large livestock numbers reduced over the period 1975-2013 [86]. Cattle numbers for Okakarara reduced from 90,539 to 87,971. However, at times cattle numbers were as high as 128,454 in 1977. Other large livestock numbers, i.e. horses, donkeys and game showed little to no mentionable decline for the Okakarara district. By 2013 small livestock numbers, i.e. goats and sheep, increased to almost double the amount reached in 1975. Cattle numbers in Otjiwarongo reduced from 160,486 to 72,033; but were as high as 189,350 in 1972. Small stock livestock numbers, i.e. goats and sheep, in the Otjiwarongo district showed similar decline over the period

1971 to 2013. Other large livestock numbers (horses and donkeys) remained stable over the said period.

In general, and as specifically discussed in section 4.1.1, farmers and authorities see a strong relationship between annual total rainfall, annual livestock output and bush encroachment. This relationship was tested based on data presented; a direct relationship could not be found (section 6.1). Livestock data analyses for the Okakarara and Otjiwarongo production areas are presented in Table 5-13. Data is analysed in EViews®8, in the same manner as rainfall data analyses were carried out (Table 5-12). Table 5-13 shows the results for cattle data analyses only; in a similar manner, small livestock and other large stock data analyses were undertaken. The combined commercial livestock numbers are presented in Table 5-14.

Table 5-13 Large livestock data analyses and results for the Okakarara and Otjiwarongo production areas for the period 1971 to 2013

Data type analysed	Data test conducted	Test result	Conclusions & Remarks
Cattle data series for **Okakarara**	ADF (unit root test)	t-stat critical value at 1% confidence level v's t-stat result: **-2.95 > -3.64 for 40** observations after adjustments (1973-2013)	Reject that cattle numbers have an unit root; therefore data series is **stationary, at 1% confidence level**.
Cattle data series for **Otjiwarongo**	ADF (unit root test)	t-stat critical value at 10% confidence level v's t-stat result: **-2.31 > -3.62 for 42** observations after adjustments (1971-2013)	Reject that cattle numbers have an unit root; therefore data series is **stationary, at 10% confidence level**.

Data series for small livestock units and other large livestock units are stationary. Livestock numbers were not continuously documented by authorities for the period 1970 to 2013; no livestock numbers were available for all farmland areas for the years 2007, 2008 and 2009. Interpolation was used to estimate these years' cattle numbers for modelling wood-based biomass resources and to match available data for rainfall. The livestock data series of Okakarara and Otjiwarongo are stationary; it can therefore be assumed that the livestock numbers will return to the long term average number over time, considering also rainfall patterns and harvesting of bush (section 6.1.1). The time series for livestock numbers and rainfall in Okakarara and Otjiwarongo which were used for wood-based biomass modelling is presented in

Table 5-14. Conversion ratios (section 3.4.7) were used to derive at the total livestock numbers equivalent to large livestock units. Interpolation was carried out in EViews®8 using the interpolation function of the software for each of the data sets where data was missing. For dates before 1971, too many annualised data sets were not provided, rendering the data series unreliable and thus data before 1971 was not used.

Table 5-14 Time series for rainfall (mm/a) and all livestock roaming on farmland for the Okakarara and Otjiwarongo production areas for the period 1971 to 2013

	Okakarara		Otjiwarongo	
Time (year)	**Rainfall (mm/a)**	**LSU-equivalent**	**Rainfall (mm/a)**	**LSU-equivalent**
1971	362.0	76,063 (interpolated)	486.4	180,584
1972	275.0	77,028 (interpolated)	381.9	207,488
1973	167.6	82,415	276.3	158,838
1974	664.4	94,036 (interpolated)	728.8	113,297
1975	405.1	105,656	364.0	138,175
1976	613.3	105,657	622.5	136,700
1977	525.0	142,687	511.7	132,614
1978	603.0	122,407	572.5	140,488
1979	520.1	115,155	492.7	123,686
1980	237.5	101,387	332.2	102,800
1981	215.1	113,579	187.5	87,497
1982	257.2	111,767	384.0	87,244
1983	316.0	109,162	280.7	78,658
1984	233.4	111,698	285.1	82,128
1985	229.4	120,980	456.8	93,132
1986	329.8	120,251	429.1	198,436
1987	281.3	122,406	393.5	195,228
1988	275.9	131,646	404.8	198,197
1989	324.9	124,737	276.2	83,518
1990	334.8	142,446	447.2	111,849
1991	422.9	140,482	515.1	102,274
1992	234.1 (interpolated)	100,913	152.8	112,960
1993	520.4 (interpolated)	105,718	489.1	109,730
1994	303.8 (interpolated)	110,923	338.3	99,325
1995	176.7 (interpolated)	122,326	233.4	69,481
1996	259.1	121,074	249.5	65,868
1997	575.0	114,436	522.2	70,530
1998	287.0	132,140	191.9	68,051
1999	306.3	114,585	495.3	69,484
2000	375.9	99,710	394.0	64,193
2001	404.1	102,998	382.2	66,207
2002	283.0	95,628	328.6	79,764
2003	214.3	97,879	297.5	78,861
2004	393.8	100,248	432.9	93,295
2005	284.2	100,520	434.1	90,965
2006	649.8	97,194	744.2	55,113
2007	166.4	102,026 (interpolated)	302.2	63,725 (interpolated)
2008	594.9	100,954 (interpolated)	468.7	72,337 (interpolated)
2009	317.8	102,834 (interpolated)	531.3	80,948 (interpolated)

	Okakarara		Otjiwarongo	
Time (year)	**Rainfall (mm/a)**	**LSU-equivalent**	**Rainfall (mm/a)**	**LSU-equivalent**
2010	565.1	104,714	856.2	89,561
2011	512.3	106,259	512.1	94,447
2012	410.2	116,634	398.9	86,679
2013	174.4	112,590	145.1	79,716
Average	**362.8**	**110,092**	**412.3**	**104,978**

5.1.5 Conclusions on wood-based biomass and bush encroachment related data of Namibia

Section 5.1 dealt with data requirements and availability; as well as data manipulation and relationships between data series relevant for wood-based biomass modelling in the Namibian context. Information was presented for the following types of data:

- recorded development of bush encroachment in Namibia for the period 1956 to 2013;
- status of bush encroachment in Namibia, 2013;
- factors to convert TE-units and TE-units/ha to kg and kg/ha for each declared bush encroachment species;
- potential wet-t/ha wood yield after first time harvest from each bush encroached farmland area;
- bush population annual growth rate in % over the period 1956 to 2013;
- long term average rainfall of farmland areas most affected by bush encroachment;
- carrying capacity developments for the period 1970 to 2010;
- the suggested 'optimal' level of bush coverage in TE-unit/ha;
- dynamic features of the rainfall and livestock (i.e. cattle) data and the implications for ease of modelling, and the relationship between data types.

In addition, section 5.1.3 focused on two specific farmland areas, i.e. Okakarara and Otjiwarongo where the potential wood yield from bush encroachment is high; and improvements in the livestock output are considered to be noteworthy if bush encroachment is reduced. The specific bush encroachment levels (in TE-units/ha and potential wood yield after first harvest in wet-t/ha) and potential bioenergy yields are presented in Table 5-15.

Table 5-15 Analysed potential wood yields after first time harvest of the complete farmland areas Okakarara and Otjiwarongo in 2013

Farmland area	Weighted mean bush density of all species (TE ha^{-1})	Annual bush population growth rate (%)	Potential wood yield after first harvest (wet-Mt)	HHV (MJ kg^{-1})	Potential bioenergy yield after first time harvest (TJ)	Suggested level of bush density to be left (TE ha^{-1})	Type of farmland ownership
Okakarara	4,297	3.18	27.09	18.6	503.87	2,500	non-freehold
Otjiwarongo	5,606	3.18	104.87	18.6	1,950.58	2,500	freehold

5.2 BIOMASS DATA REQUIREMENTS AND AVAILABILITY – SOUTH AFRICA

5.2.1 Review of wood-based biomass related data availability

From Chapter 4, Section 4.1.3 some selected wood-based biomass resources are available for bioenergy production via the fast pyrolysis route; others are not allowed to be used or the demand for them is in excess of their local production. For example, the demand for residues from wood chips generated by saw and paper mills outstrip the supply of the same resource (Figure 4-5); it seems that additional wood chips are sourced from elsewhere to satisfy the demand. The data and its properties are presented in the tables that follow. The total amount of wood potentially available for fast pyrolysis production is summarised in Table 5-16.

- Wood residues from commercial forestry activities, are considered to be some 20% of annual round wood production, for both softwood and hardwood together (Figure 4-6), of which half is considered to be left in the forests to decay, and half could be used for fast pyrolysis conversion.
- Wood from woodlands and bush encroachment by mainly indigenous *Acacia* species, and where livestock is reared in *Acacia* woodlands (Table 4-3), and;
- Wood and wood chips generated by the 'Working for Water (WfW)' programme through eradication of alien tree species from selected areas (Table 4-4).

Table 5-16 Analysed potential amount of wood-based biomass available for fast pyrolysis conversion

Name of wood-based biomass	Average amount (wet-Mt a^{-1})	HHV (MJ kg^{-1})	Total potential bioenergy yield (TJ)	Total energy potential (Mtoe)
Commercial forest residues after harvest for other industries (averages for period 1979 – 2008/09)				
Softwood	0.9	20.21	18.1	0.4
Hardwood	0.6	18.81	11.8	0.3
Wood from woodlands & bush encroachment (average for first time harvest)	29.7	19.31	574.2	13.7
Wood-based biomass potential harvested from alien species growing in the Eastern & Western Cape	12.9	18.41	237.7	5.68

Considering the information from Table 5-16, it seemed worthwhile to investigate the use of wood-based material from woodlands and bush encroachment, as well as the WfW programme as resource for conversion to bioenergy via the fast pyrolysis route. Wood-based biomass from commercial forestry residues at the onset seemed to deliver a resource worthwhile to consider. However, this material is disbursed over 1.3Mha, i.e. delivering approximately around 1t/ha of usable biomass. Furthermore, the forestry residues still need to be collected and piled at a more central collection point, and thereafter transported to a fast pyrolysis conversion facility. The costs of the latter seem to outstrip the potential economic benefit. Thus the use of commercial forest residues will not be investigated any further. Under South African circumstances, this research thus only investigated the use of wood-based biomass from:

- Woodlands, mainly indigenous *Acacia* types,
- Bush encroachment, mainly indigenous *Acacia* types, and
- Alien plant species growing in the Eastern and Western Cape, which are a combination of alien *Acacia* species.

5.2.2 Socio-economic, ecological and national policy indicators

The socio-economic, ecological and national policy considerations for woodlands and alien plant species have been discussed in Chapter 4, sections 4.1.4 (Woodlands and Bush Encroachment) and 4.1.5 (Alien Species). The modelling approach (section 6.2) will considered the use of wood-based material from woodlands and bush encroachment with a view to reduce bush encroachment to ecological sustainable levels. This is similar to the approach used under Namibian circumstances. Under the Working for Water (WfW) programme, alien species need to be eradicated to re-instate a bio-diverse and ecologically sustainable environment. Therefore, when all alien plant species are removed from e.g. the Eastern and Western Cape, this resource will be depleted and alternative resource material (e.g. municipal waste or other plant matter) could be used to generate energy via fast pyrolysis. WfW also has the policy objective to socio-economically develop communities, especially in rural areas. This means policies for long term job creation and value addition would need to be considered in the modelling approach (section 6.2).

5.2.3 Link to other sectors and land use issues

Under South African considerations, the linkage between wood-based biomass and bioenergy production for e.g. industrial use is weak [7] (section 2.5.4.2) on the one hand. On the other hand, the linkage between eradication of alien plant species for improved land use options and biodiversity is strong [7, 60; 163]. The results of biomass modelling and fast pyrolysis technology modelling will possibly provide impetus to positively link biomass production with bioenergy production also for industrial use; keeping various policies in mind (e.g. on climate change).

5.2.4 Spatial indicators

Woodlands from which wood-based biomass needs to be harvested and bush encroachment are occurring in the highland areas of South Africa, i.e. in the Limpopo, Mpumulanga and Northwest Provinces. The wood-based biomass to be harvested from alien species is located in the Eastern and Western Cape, with the greater part occurring in the Eastern Cape. The distance between the resources are long, i.e. more than 800km. This may lead to high logistical costs to transport and store resources at one location. It would thus be necessary to consider if only one, or more than one fast pyrolysis conversion plant is economically viable to produce bio-energy (section 6.2 and 8.1).

5.2.5 Dynamic features of the data

Unlike the situation in Namibia, woodlands and bush encroachment data have not been captured continuously. Data is captured and presented in maps for purposes of explaining coverage; the data is freely accessible. However, the data presented in such maps, is 'only' a presence/absence indicator of all woodlands species, including declared bush encroachment species. The number of sightings cannot be related to wood density, but rather to presence of people having sited the occurrence of such species.

The work of Smit [79] provides an indication on how to translate standing biomass, expressed as canopy-cover (%), into wood densities (TE-units). The biomass data available can be used to derive wood yields, in wet-t. The methodology used to analyse the data and build the biomass model is similar to that used in the Namibian bush encroachment situation and discussed further in section 6.2. The average wood yield at first harvest was said to be some 15t/ha [79].

In terms of the use of wood-based biomass from alien species, the data presented by the WfW programme presents itself with a declining trend (i.e. non-stationary) as it is the Government's aim to eradicate these species over time. Section 6.2 discusses how sufficient biomass resources could be made available by using biomass from alien plant species to sustain a fast pyrolysis conversion operation for the longest possible period of time.

5.2.6 Conclusions on wood-based biomass data of South Africa

Based on the above discussions, biomass from woodlands, including bush encroachment from the Limpopo, Mpumulanga and Northwest Provinces; and alien species from the Eastern and Western Cape were considered for biomass modelling by this research. The potential wood yields are indicated in Table 5-16.

5.3 TECHNO-ECONOMIC DATA REQUIREMENTS AND AVAILABILITY – NAMIBIA

Data on manufacturing capability, technology performance and their respective cost indicators is required to determine the viability of fast pyrolysis operations in Namibia. Data with reference to fast pyrolysis operations is not available as fast pyrolysis projects have not been piloted or operational in Namibia to date. Therefore references to gasification projects or slow pyrolysis operations were made; this subsection draws upon information as presented in the literature review, section 4.3, and specifically Table 4-6.

In Namibia [282], a national wood-based biomass gasification project was launched in 2007/8; the project was only marginally operational, after donor funding was stopped. Indigenous bush encroachment species are used in a gasifier [283] to produce 250kW power output to a community. The power was intended to be fed into the grid. The project was part of a pilot to test the feasibility of the concept and technology performance to establish further scale gasification plants to produce power either in a decentralised manner for a specific community, or to feed power into the national grid under an 'independent power producer' license. The project was initially driven by the Desert Research Foundation of Namibia, a private foundation with the aim of sustainable ecological management. Until March 2015, the project is driven by the owner of the land on which the project was established; its economic viability was not proven. The gasifier itself is still functional, and it was proven that wood can be gasified to produce electricity. Unfortunately, delivery of the generated electricity for distribution failed due to the lack of the regional electrical distributors' (REDs) commitment to have installed an appropriate transformer to feed the electricity generated into the national grid in a stable and reliable manner [282]. The pilot project was funded through the European Development Fund Nine (EDF9) [282], where the main aim is not economic viability but poverty alleviation of rural communities by introducing technologies for self-reliance.

Large scale slow pyrolysis conversion technologies were operated successfully in Namibia in the past. The technology was mainly based on retort conversion processes; nowadays technology is based on kiln conversion processes only. The diversity of technology and its performance are summarised in Table 4-6 (Chapter 4, section 4.3).

In light of the aforementioned, this research considers that there is manufacturing capability in Namibia; and that fast pyrolysis technology will perform similarly as elsewhere, e.g. in Europe. However, as fast pyrolysis technology is new to Namibia, a higher factor for total capital employed (TCE) [327] to build a fast pyrolysis plant in Namibia, as compared to one build in the USA or Europe will need to be used. Appropriate skills, political commitment towards the utilisation of new technologies seem to be essential elements to deploying new technologies [39]. Details on the costing approach associated with building and operating a fast pyrolysis plant, and the assumed manufacturing capability and technology performance are provided in Chapter 8 and 9.

5.3.1 Socio-economic, ecological and national policy indicators

Namibia's policy environment is conducive for manufacturing activities and to increase the technological adaptability and performance in general [6, 16, 90]. The Government of the Republic of Namibia supports manufacturing activities through taxation based incentives [284] and the "*Industrial Upgrading and Manufacturing Programme (IUMP)*" [285]. On taxation based incentives, only new or substantially expanded and/or diversified manufacturing activities of registered companies are eligible to apply for registration as "manufacturer" or obtain "manufacturing status" with the Ministry of Industrialisation, Trade and SME Development (MITSD). Approval to benefit from taxation based incentives is then provided by the Ministry of Finance. The IUMP, offered through the Namibian MITSD, is an application and techno-economic assessments based direct financial grants programme, which is implemented with the assistance of the United Nations Industrial Development Organisation (UNIDO). The maximum grant provided depends on the recommendation based on the assessment, but does not exceed NAD15 million per application. The establishment of a fast pyrolysis operation in Namibia would likely be able to be registered as manufacturer and/or benefit from the IUMP. However, grants or subsidies are dealt with on a case by case basis, and are not guaranteed. Therefore, for this research the costing approach does not consider incentives or financial grants in establishing the feasibility or viability of fast pyrolysis.

According to environmental and ecological regulations in Namibia [286], before setting up a new or expanding an existing exploration activity, industrial conversion factory or manufacturing plant, an environmental clearance certificate must be obtained. The certificate is to be obtained from the Namibian Environmental Commissioner. Upon screening the application for an environmental clearance certificate, the Environmental Commissioner decides if an assessment is required. The steps to be followed for an assessment include:

- scoping – the Environmental Commissioner decides on the scope and procedure for the assessment;
- environmental impact assessment (EIA) – the proponent carries out the assessment and summits an assessment report to the Environmental Commissioner;
- public consultation – persons who may be affected by the activity are notified and given a chance to inspect the assessment report and make submissions on it;
- review – the Environmental Commissioner reviews the application for the environmental certificate. This process can include further consultations or investigations;
- decision on certificate – the Environmental Commissioner decides on whether or not to grant the environmental clearance certificate.

The EIA must be carried out by an independent party, i.e. a professional or team of professionals not associated with the technical or financial viability or business plan of the project. The costs involved depend on the size of the team of professionals and complexity of the project. Table 5-17 and Table 5-18 provide an overview of indicative costs associated with carrying out an environmental impact assessment to obtain an environmental clearance certificate before the commencement of construction of a new fast pyrolysis conversion plant in Namibia. The information on cost indicators to carry out an EIA was obtained by sourcing quotations of possible service providers.

Concurrently to negotiating access to the biomass in both, the Okakarara and the Otjiwarongo districts, an environmental clearance certificate needs to be obtained for each site where harvesting of biomass would take place [286]. Obtaining such environmental clearance license is the responsibility of the owners and/or project promoters. An EIA for fast pyrolysis conversion in Otjiwarongo town needs to be carried out and approved before its operationalization. To successfully conclude agreements to access the biomass and utilise it, it is suggested to appoint a lawyer, or a group of lawyers as well as a land valuator. The costs involved are summarised in Table 5-15.

Table 5-17 Indicative rates to carry out an environmental impact assessment (EIA) for a fast pyrolysis conversion plant in Namibia (at 2012/13 market prices)

Type of professional	Daily Rate (NAD)	Hourly Rate (NAD)
Environmental Assessment Practitioner	from 10,000	from 1,500
Ecologist/ Rangeland Scientist	from 4,500	from 500
Hydrologist/ Geo-Hydrologist	from 5,000	from 600
Soil Scientist	from 7,500	from 1,000
Agricultural Engineer	from 10,000	from 750
Site Rehabilitation Specialist	from 10,000	from 750
Specialist for accreditation under e.g. FSC or ISO 14000 *(no expertise available in Namibia)*	from 12,000	from 1,500

Table 5-18 Other than directly related to the engagement of professionals, cost indicators to carry out an environmental impact assessment (EIA) for a fast pyrolysis conversion plant in Namibia (at 2012/13 market prices)

Type of expense	Rate (NAD)	
Travel		
Road transport, 4x4 vehicle	from 4.50/km	
Domestic air transport, return flight	from 3,500	
International air transport, return flight	from 8,000	
Accommodation, bed and breakfast type	from 500/ overnight	
Per diem (costs other than travel & accommodation)	from 200	
Public hearing and/or workshop	**per day**	**per hour**
Venue hire	from 1,500	from 300
Refreshments (per participant)	from 360	from 50
Audio-visual material hire (per type of equipment)	from 1,000	from 100

5.3.2 Link to other sectors and land use issues

The considered fast pyrolysis operations under Namibian conditions focused on the farmland areas of Okakarara and Otjiwarongo (section 5.1.5). Biomass use in the Okakarara district is guided by land use options for Okakarara, and need to consider traditional, communal land use rules and regulations. This means, that the Okakarara Traditional Authority would need to provide the authorisation first, then only would the Namibian Government issue a license allowing the use the wood-based biomass. The Okakarara Traditional Authority would guide the rate at which the biomass may be removed; and determine the price to be paid per unit wet-weight of biomass. The biomass would be harvested from the Okakarara district; fast pyrolysis conversion would take place in Otjiwarongo town area or on a commercial (freehold) farm in the Otjiwarongo district area.

Wood-based biomass use in the Otjiwarongo district is guided by land use options for the Otjiwarongo commercial farmland area. This means, land titles are registered as freehold land and land owners themselves can guide the use of wood-based biomass, and determine the price to be paid per unit wet-weight of biomass. Biomass removed from Otjiwarongo freehold land will be transported to Otjiwarongo town; fast pyrolysis conversion would take place in Otjiwarongo town or on a commercial (freehold) farm in the Otjiwarongo district area.

Table 5-19 Professional fees for lawyers and land valuators in Namibia (at 2012/13 market prices; rates are indicative only)

Type of expense	Rate (NAD)
Lawyer	From 3,500/ hour
Land Valuator	From 3,000/ site valuation
Out of office rates	As indicated in Table 5-16

5.3.3 Spatial indicators

5.3.3.1 Harvesting considerations and indicators

By policy direction [81] the socio-economic and ecological sustainable state of Namibian rangelands needs to be achieved; a time horizon is not provided. to ease modelling, a time horizon of at least 20 years was considered, because:

- the affected farmland area is very large and interventions are expected to be very resource intensive (human, financial, equipment, logistics, time for planning and execution);

- downstream activities which can utilise the wood-based biomass resource need to be considered for their feasibility and viability under a set of useful parameters like typical project loan periods, technical lifespan of equipment, taxation regime ; and
- positive socio-economic and ecological impact of reducing bush encroachment would be expected to be noticeable and measurable, notably e.g. with the Vision 2030 economic policy planning frame.

Bush encroachment is lessened by various types of harvesting and/or clearing methods (Table 5-20). Clearing methods used in Namibia involve manual, semi-mechanised, mechanised and arboricide application methods. The most common method is manual clearing and application of some kind of arboricide. Manual clearing involves labourers who use non-mechanised hand-tools to slash or cut bush; hand-tools are most commonly axes and pangas (a type of machete). The tools are easy to handle, relatively cheap and of very low maintenance.

Arboricide application is commonly used for thinning heavily infested areas to gain some access to that land and as a follow up or aftercare treatment after manual or types of mechanised clearing. Though selective killing of trees is not guaranteed and non-encroaching bush or tree species may also be killed in the process. There are various types of arboricides available on the Namibian market (pellets, liquids and suspension concentrates). Application of arboricides is either by manual distribution of pellets or spraying (large scale aerial application of arboricides was discontinued in the early 1990s). The arboricides sold in Namibia are either photosynthesis blockers or disrupters. The use of arboricides is continuously monitored as there is the possibility that metabolites of such may be traced in especially beef [287]. The guidelines followed by Namibian authorities for monitoring arboricide use are informed by the Environmental Protection Agency (EPA) based in the USA.

Table 5-20 **Bush harvesting and clearing methods used in Namibia, their costs, effectiveness and environmental impact caused**

Bush harvesting or clearing method	Equipment or other means used	Approximate time and minimum amount of personnel required to clear 1ha of bush at 2500TEha^{-1}	Impact/effect of clearing method on environment	Ease of utilising the method and season in which method is recommended to be used	Can wood material still be of use to fast pyrolysis after method is used?	Approximate cost of method (NADha^{-1}, at 2012/13 prices), incl. labour and equipment
Veld burning	Matches, fire-clap, some dry plant material to start fire off, water	1 day, must be a team of 6-8 persons to monitor and control fire	All plant material is burnt at once; but regrowth of “wanted” plant species is vigorous	Unskilled people should not do this; supervision is necessary as there is great risk for fire to become uncontrolled; only to be done between July and September	Unlikely as most material would be charred or partially charred; better to leave plant material behind for soil and small fauna nutrition	<200
Stem burning	Matches, some dry plant material to start fire off, shovel, water	>7 days; can be done single handed or in teams; time to clear reduces as team size increases	Selective invasive tree/bush species are burnt only	Semi-skilled persons can carry this out; each stem must be extinguished after being burnt down; only to be done between May and September; recommended to be a follow up or aftercare treatment only (after manual, semi-mechanised cutting)	Unlikely as material would be charred; better to leave plant material behind for soil and small fauna nutrition	~900
Manual arboricide application (pellets)	Arboricide, protective clothing	1 day, 1 person	Selective invasive tree/bush species are to be treated only	Half-life of arboricides vary between 6 weeks and over 24 months; arboricides that have a	Yes; arboricides application is advised to be used only as follow up	546-712

Bush harvesting or clearing method	**Equipment or other means used**	**Approximate time and minimum amount of personnel required to clear 1ha of bush at 2500TEha^{-1}**	**Impact/effect of clearing method on environment**	**Ease of utilising the method and season in which method is recommended to be used**	**Can wood material still be of use to fast pyrolysis after method is used?**	**Approximate cost of method (NADha^{-1}, at 2012/13 prices), incl. labour and equipment**
Manual arboricide application (liquids or suspension concentrates)	Arboricide, water (or suspension liquid like Diesel), syringe, pump (in a rucksack), protective clothing	1 day, 1 person	Selective invasive tree/bush species are to be treated only	long half-life remain active for a longer period of time and have a greater potential for contaminating groundwater supplies in semi-arid zones (like Namibia); desired tree/plant species may also be killed through groundwater contamination; health hazards are not fully known; arboricides are only effective if applied just before the rainy season starts	or aftercare treatment; cutting dry wood material is extremely cumbersome and expensive (due to high maintenance costs on equipment)	550
Manual cutting	Axe, panga, protective clothing	4-7 days, 2 persons (1 cutting, 1 dragging and compiling wood)	Selective invasive tree/bush species are cut only	No negative impact on environment; also creates many jobs for unskilled and semi-skilled labour; can be done throughout year, but best if done from May to November, to better prevent bush from coppicing	Yes, though wood should still be comminuted and dried to the right size	670 – 700

Bush harvesting or clearing method	Equipment or other means used	Approximate time and minimum amount of personnel required to clear 1ha of bush at 2500TEha^{-1}	Impact/effect of clearing method on environment	Ease of utilising the method and season in which method is recommended to be used	Can wood material still be of use to fast pyrolysis after method is used?	Approximate cost of method (NADha^{-1}, at 2012/13 prices), incl. labour and equipment
Semi-mechanised cutting OR chipping	Chainsaw, axe, panga, protective clothing; and for semi-mechanised chipping, a chipper, fed manually	1 day, 2 persons (1 cutting, 1 dragging and compiling wood)	Selective invasive tree/bush species are cut only	No negative impact on environment; also creates many jobs for unskilled and semi-skilled labour; can be done throughout year, but best if done from May to November, to better prevent bush from coppicing; trees/bushes must be still alive to save on maintenance costs of equipment and tools	Yes, though wood should still need to be comminuted and dried to the right size	700 – 1,000
Fully mechanised operations (incl. felling, chipping, compiling and often comminution)	Bulldozer OR mechanised feller and chipper; protective clothing	<½ day; 2 persons (1 driver, 1 scout to lead through terrain)	Unselective clearing with great potential damage to soil (compaction and other disturbance); danger that very invasive species like *Dichrostachus cinerea* regrow and spread even more vigorously, especially when bulldozers are used. An EIA must be in place prior to harvesting commencement.	Only to be done by skilled and trained persons; can be done throughout the year, and when bulldozers are used, recommended to be done for making roads and protective/access fire-strips only	Unlikely if bulldozer was used; rather costly to sort wood from piles of debris. Yes, if mechanisation involves tree/bush felling, chipping and compilation.	1,000 – 1,100 (felling, chipping, compilation) 2,000 – 4,000 (clearing by bulldozer)

Large scale contracting for bush clearing, compiling and wood processing is done occasionally only. As an example, bush clearing and processing for energy production for a cement factory in the Grootfontein farmland district [112] is done at large scale. The bush harvesting and clearing is an activity commonly carried out in the interest of the farmland owners and as source of energy for the cement factory respectively. The farmer would pay an agreed amount per tonne of wood removed, and the cement factory or its subcontractor(s) would extract the wood as source of energy. The company [111] clears about 5kha land annually, with the available environmental clearance certification for the specific farmland areas. This model is a good solution where farmers do not possess the equipment or capacity to clear bush, yet have an interest to do so. This model can co-exist alongside the methodology proposed in the research. As a large quantity of wood is required annually (some 80kt), the cement also source wood from third parties to augment its own supply.

Small scale contracting for bush clearing and/or harvesting with wood processing takes place more regularly. For example, the farmer would pay for the arboricides and farm workers to apply arboricides; the bush is left to dieback and not utilised thereafter. A similar case is with stem burning or veld burning – the farmers do not readily use the wood after burning. Where manual cutting is involved, usually also contract harvesting or clearing is done for the production of charcoal on such farm. In the latter case, contract labourers are engaged to manually fell bush, cut the wood to size and compile it to dry prior to the charcoal making process. The charcoal is made in the Namibian Bush Drum Kiln. The labourers in this case are paid on a per-tonne charcoal produced and not how much land was cleared of bush; a practice that is often problematic [116]. Problems relevant to this research include;

- <u>labour dissatisfaction</u> due to very low prices paid for the charcoal in relation to the price the farmer obtains for the same charcoal;
- <u>negative environmental impact</u>: it is easier to cut and use larger trees (diameters above 15cm at knee-height) for charcoal making than thinner (diameters between 5 and 15cm at knee-height) and shorter bushes; charcoal from larger trees is more lumpy and heavier than from smaller bushes; and uncontrolled veld fires can be caused by the rather primitive charcoal making process as no protective barriers are set between the site where charcoal is made and the rest of the veld where bushes are being harvested.
- <u>Seasonality</u>: farmers who have a bush encroachment problem usually know they need to do something about it, but may not have the financial means due to fluctuating income

streams in the farming business; therefore labourers are only engaged when the farmer has spare cash available.

5.3.3.2 Infrastructure, logistics, handling and storage indicators

Indicators and data on infrastructure, logistics, handling and storage are required to cost the setting up of fast pyrolysis conversion facilities in Namibia; from harvesting the wood-based biomass (bush) to marketable product (bio-oil). Table 5-21 and Table 5-22, summarise the various indicators, expressed as costs Namibian Dollar (NAD or N$) per unit associated with infrastructure, logistics, handling and storage. Infrastructure includes, e.g. various types of buildings required to operate a fast pyrolysis plant; logistics includes, e.g. the types of equipment or modes of transport to forward input materials to and products from the production site; handling includes e.g. type of equipment to forward input materials and products on the production site; and storage includes, e.g. the stock holding, either as input material or product on site.

Table 5-21 Infrastructure indicators (at 2012/13 market prices)

Type of infrastructure	**Costs NAD/unit**	**Costs/unit (rental or lease hold)**
Property costs		
Industrial, urban land within Otjiwarongo (for fast pyrolysis plant)	800/m^2	not applicable/ not available
Industrial, rural land	161/m^2	
Commercial farmland in Otjiwarongo district area	From 4,000/ha	Usually calculated on basis of market value; approximately 1% of purchases price/ month
Building costs		
Offices	5,000/m^2	100/m^2
Industrial shell	3,000/m^2	
Shed	1,000/m^2	
Ablution facilities	3,000/m^2	
Roads construction		
Tarred	from 1,000,000/km	not applicable
Gravelled	from 500,000/km	not applicable

Type of infrastructure	Costs NAD/unit	Costs/unit (rental or lease hold)
Fast pyrolysis plant; excludes electricity generator and grid connection		
1t/h	Costs to be modelled by this research (Chapter 8)	not available
from 5t/h	Costs to be modelled by this research (Chapter 8)	not available
Furniture and fixtures (average, lump sum per person employed)	from 10,000/ person	not applicable
Internet and communication technology (ICT); hardware only Average, lump sum per person employed	from 15,000/ person	not applicable

Table 5-22 Logistics and handling indicators (at 2012/13 current market prices)

Type of logistics	Costs (NAD) /unit	Costs (NAD)/unit (rental)
Transport		
On-farm/ on-site handling & transport (e.g. tractor-trailer combination; forklifts)	20/ running-km	--
Transport of products ex-farm or ex-factory to market	34/ freight-km	--
Grader (on-site & on-farm road maintenance)	not recommended	600/h
Bulldozer (for on-site & on-farm road maintenance)	not recommended	from 1,000/h
Storage equipment and related costs		
Stainless steel tanks (for bio-oil)	from 200,000/ 2,500l tank	Not recommended
PVC tanks (for bio-oil)	from 3,500/ 2,500l tank	Not recommended
Biomass stockholding	5% of biomass purchase price	--

5.3.4 Techno-economic indicators

The information (data) on the biomass physical and chemical properties is provided in detail in Chapter 7. Personnel and commensurate skills/expertise requirements in general for all operations (bush harvesting, logistics, conversion process and administration) are discussed in Chapter 8 and 9.

For calculations on capital requirements, the following information was considered:

- Commensurate with the harvesting cycle of 20 years, the life of the project is also 20-years.
- The long term reposition rate (i.e., repo rate following a target band for consumer price index of between 3 to 6%) moves in a target band of between 3 and 6%.
- The spread between repo rate and the prime interest rate is not to exceed 375 basis points (a Bank of Namibia policy directive from 2010).
- Financial institutions usually charge a market interest rate which is based on the prime interest rate plus a mark-up, resulting in a 10-12% interest rate on loans. However as market long term interest rates on loans can vary significantly and past trends have favoured high-end interest rates, 12% is assumed a realistic value to use.
- All costs for the pyrolysis equipment have been calculated for 2012/13, based on $€_{2010}$-rates and converted to Namibian Dollars (NAD or N$); capital and operational costs have been calculated for 2012/13 based on $€_{2010}$-rates and converted to Namibian Dollars (NAD).
- Plant life is based on prior track record and commercial experience of the technologies, and for fast pyrolysis 80% availability is assumed.
- European based costs for equipment (assuming that essential plant parts will be bought and imported from the EU).
- For modelling *a priori* base case feedstock costs are set at NAD100/wet-t at central collection point. The cost recovery feedstock price will be determined by solving the model. VTT report data [102] suggest a range of NAD180-220/dry-t bush delivered to 10 MW electricity output fast pyrolysers.
- Shipping and other transportation costs for conversion plants, or parts thereof, from Europe to Namibia are not included in the costs. These were assumed to be included in commissioning costs.
- Compliance with EU emissions standards for NO_x, SO_x, particulates, VOCs and CO.

- Grid connection costs have not been incorporated nor land purchase costs (understanding is that these will be very low relative to the plant cost).
- Fees for disposal of residues only.
- All electricity production cost estimates are pre-tax, no incentives (e.g., no CO_2 credits through Clean Development Mechanism (CDM) or carbon sequestration by burying char in the soil, no capital allowances or tax breaks in the first optimisation calculations of the model). Environmental credits were not provided to CDM projects to date; and the Kyoto Protocol lapsed in 2012. It is therefore assumed that no environmental credits will be provided in future. E.g. the cement factory [112] applied for such based on an energy supply switch from fossil fuels to biomass based energy and was denied such.
- No financial incentives or subsidies or other environmental credits.

Apart from the spatial considerations provided above, the assumed techno-economic indicators for Namibia, used in the assessment are summarised in Table 5-23.

Table 5-23 Calculation factors used in the techno-economic assessment of a fast pyrolysis conversion operation, adapted from [116, 288]

Description	Calculation factor
No of plant replications	1
Life of project (years)	20
Base case feedstock costs (ZAR or NAD/t)	100
Bank reposition (repo) rate (%)	6
Prime interest rate (%; repo rate +375 basis points) on loans	9.75
Market interest rate (%) on loans	12
Market interest rate (%) on deposits	4
Long-term inflation rate (%)	6
Corporate income tax rate (%)	29
Management rate (NAD/year)	450 000 per person
Labour rate (NAD/year)	70 000 per person
No. of shifts	4 (3 shifts on, 1 on rotation)
Overhead cost (%Capital Costs (CC)/year)	7
Maintenance (%CC/year)	10
Availability (hours/year)	6960
Capital allowances	None
Exchange rate (NAD:ZAR; NAD is pegged to ZAR)	1:1
Exchange rate (EUR:NAD); average 2010-2014	10:1
Exchange rate (GBP:NAD); average 2010-2014	12:1
Exchange rate (USD:NAD); average 2010-2014	8:1

Table 5-24 Utility costs and other reagent and techno-economic data for a fast pyrolysis plant

Parameter	Value
Fluidisation and Cooling Costs	
N_2 (NAD/t)	200
(Dry ice)	
Utilities-Services	
Water charge – supply (NAD/m^3)	23 plus a base charge of 30
Water disposal charge-Reception (NAD/m)^3	25
Water disposal charge-Biological (NAD/m^3)	30
Plant ash (NAD/t)	75
Hot gas filter residues (NAD/t)	50
Transport costs (NAD/t)	100
Municipal refuse removal (NAD/month)	184
Bulk electricity (per 3-phase connection)	
Deposit (NAD)	3,000
Network charge (NAD)	550
Capacity charge (NAD/amp)	32.40
Usage (NAD/kWh)	1.61
Energy Levies (NAD/kWh)	0.2252

5.3.5 Data sourcing and dynamic features of the data

All cost indicators exclude factors for or costs associated with value added tax, import or export duties and taxes; governmental subsidies or taxation based incentives, discount rates or professional fees payable for design, project management, installation, commissioning and training. All indicators are obtained from dealers and service providers, either in Namibia, South Africa or Europe. Price indicators are spot prices, and current market prices for the year 2012/13. Adjustments to the data are not necessary. The model (Chapter 8) takes account of prices which may change over time mainly due to inflation. The viability calculations are based on cost-benefit analyses, that is, net present value (NPV) determination.

5.4 TECHNO-ECONOMIC DATA REQUIREMENTS AND AVAILABILITY – SOUTH AFRICA

All cost factors as presented for the Namibian case, are also applicable for South Africa, except where indicated. This is due to legislative requirements and/or market related differences; either is indicated under the relevant sections.

5.4.1 Socio-economic, ecological and national policy indicators

The Government of South Africa has deployed a range of complementary and integrated measures to grow the economy and create jobs. The latest Industrial Policy Action Plan (IPAP) 2014/15 - 2016/17 [289] is one of the key pillars of the socio-economic development plans of the South African Government. The IPAP is revised annually, and presents a three-year rolling IPAP with a 10-year outlook in the overall economic development context. The South African government promotes that the IPAP analyses the latest trends in the global and regional industrial policy for optimal policy coherence within Government, between government departments and across a full range of stakeholders and social partners.

The IPAP 2014/15 - 2016/17 highlights the importance of the forestry, timber, paper, pulp and furniture; and biofuels industrial sectors. Within the forestry sector, e.g. mechanical conversion of wood-based resources is promoted, in terms of addressing raw material supply and; yield and productivity improvements in this sector. The focus of the biofuels sector is on

> '*accelerated development in the biofuels sector by leveraging the Regulations on Mandatory Mixing of Biofuels with Petrol and Diesel which is due to come into operation from the 1st October 2015*'.

The South African government aims to support the production of biofuels feedstock in seed production for soybean and sorghum. The intervention is based on the economic rationale to make biofuels production commercially viable, and the biofuels sector's linkages to agriculture and manufacturing, with the potential to especially create jobs in the agricultural sector. However, thermo-chemical conversion of wood-based biomass or deriving energy from wood-based biomass is not mentioned in the IPAP 2014 - 2017, and therefore it is assumed that such activities would not likely attract state support, or need additional motivation before support is granted.

Authorisation to engage in renewable energy projects requires compliance to a number of ancillary legislations. These are presented in Table 4-5, and all are relevant to fast pyrolysis conversion of wood-based biomass into energy. Environmental authorisation for any given activity would only be granted by the component authority after the developer has complied with the procedural requirements as set out in the environmental impact assessment (EIA) regulation of the NEMA [125, 179], and they must be carried out by an independent and competent environmental assessment practitioner. The environmental impact assessment and authorisation processes take about one-and-a-half to three years. The procedural length induces great uncertainty for investors; some may choose to discontinue any investment plans [290]. The costs associated with environmental impact assessments are comparable to those of Namibia (Table 5-17).

5.4.2 Link to other sectors and land use issues

Fast pyrolysis operations under South African conditions were focused on the alien species invaded areas of the Eastern and Western Cape, as well as *Acacia* type biomass from bush encroachment areas predominantly located in the Limpopo, Mpumulanga and Northwest Provinces of South Africa (section 5.2.6). Biomass use in South Africa is guided by the socio-economic planning and environmental legislative measures as described in Table 4-5 which summarises the link to other sectors. Cost factors and the costing approach under South African circumstances are comparable to those in Namibia.

5.4.3 Spatial indicators

5.4.3.1 Infrastructure, logistics, handling and storage indicators

Generally farmland units in South Africa are much smaller than those in Namibia. In Namibia, economically viable farming units (depending on the ecological zone) are multiples of one-thousand hectare per farm. In South Africa, economically viable farming units range from 5 hectare up to some 300 hectare per farm for crop farms, or some 1,000 hectare for a large livestock farm. Farmland is South Africa is far more expensive than that in Namibia. The price factors are provided for the provinces Eastern and Western Cape, Limpopo, Mpumulanga and Northwest Provinces.

Table 5-25 Infrastructure indicators (at 2012/13 current market prices)

Type of infrastructure	Costs/unit (purchase price)	Costs/unit (rental or lease hold)
Property		
Industrial, urban land (for fast pyrolysis plant) (ZAR/m^2)	from 15,000	not applicable; model to be ownership based
Farmland (ZAR/ha)	from 500,000	

5.4.4 Data sourcing and dynamic features of the data

Data was sourced from national economic and market reports as published by national authorities, like Statistics South Africa and Central Government Departments. Prices are provided without value added tax (VAT) and presented as real market price-average for the calendar years 2012-2014. All techno-economic cost calculations will be presented without VAT and not considering, subsidisation, taxation or cash grant based incentives as may be provided by the South African government (Chapter 8 and 9).

5.5 MARKET RELATED DATA REQUIREMENTS AND AVAILABILITY – NAMIBIA

5.5.1 Socio-economic, ecological and national policy indicators

Namibia aspires to be energy self-sufficient by 2030 [16], i.e. to provide for the country's own electricity demand and, to a certain extent, liquid fuel demand. The goal of "own electricity supply" is to be achieved by enhancing the electricity generation and transmission capacity of the national power supplier, NamPower. In addition, a conducive policy and economic environment for independent power suppliers at national and regional level is to be provided; export of surplus electricity to neighbouring countries is a consideration, once domestic demand is satisfied. The electricity demand forecast is presented in Figure 5-9 [2, 291, 292].

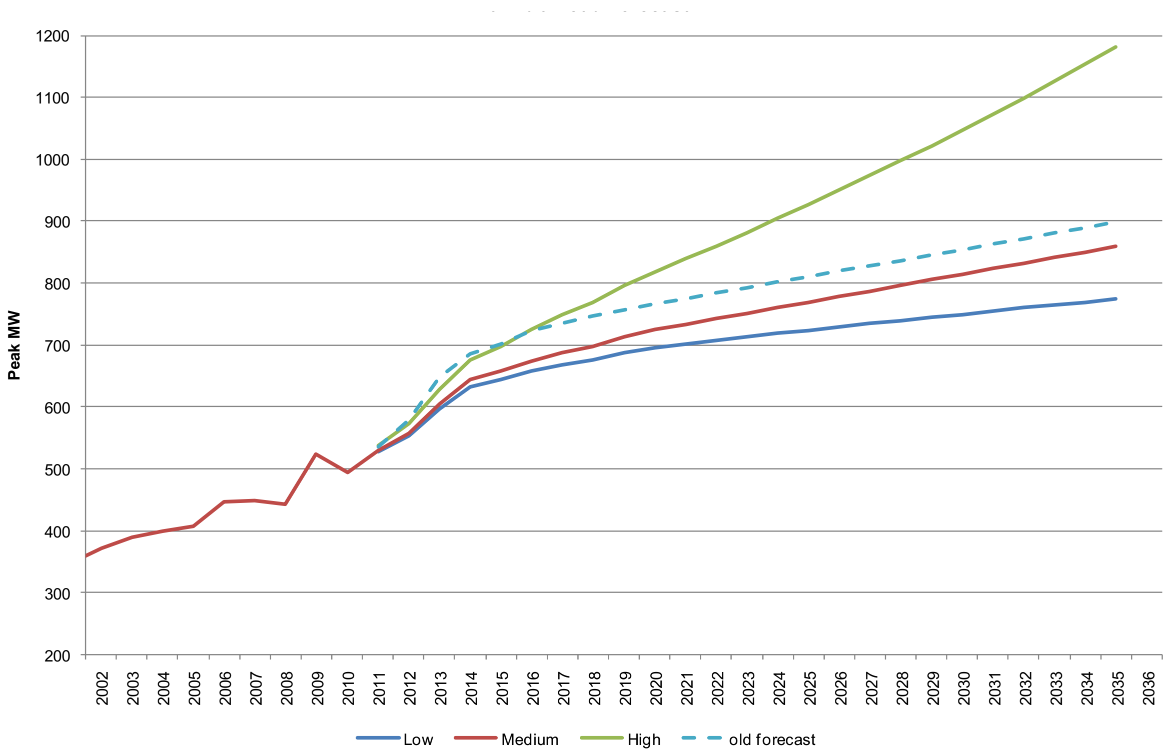

Figure 5-9 Electricity demand forecast until 2036 [2]

As visualised by Figure 5-9, demand for electricity is increasing; supply though remains a challenge and alternative electricity supply initiatives are being considered and promoted by the Namibian Electricity Control Board (ECB) [292]. In April 2014, the ECB proposed renewable energy feed-in tariffs (REFIT) and rules [293]. The proposed REFITs for electricity generated by biomass are presented in Table 5-26. These proposed REFITs will be used in the techno-economic modelling of fast pyrolysis for electricity generation (Chapter 8 and 9).

Table 5-26 Proposed REFITs for electricity generated by biomass in Namibia [293]

Proposed REFIT (NAD kWH^{-1})	Proposed REFIT (US cents kWh^{-1})	for plants with an installed capacity of (MW)
2.04	18.8	0.50
1.97	18.1	0.75
1.90	17.4	1
1.61	14.8	2
1.37	12.6	3
1.30	12.0	4
1.23	11.3	5

For liquid fuel, the goal is mainly to have sufficient bulk storage capacity for the liquid fuel types, i.e. petrol, Diesel and heavy furnace oil; an equivalent of six-months' of the country's demand of various types of liquid fuel. The Government of Namibia has tasked the National Petroleum Corporation (NamCor) to facilitate bulk storage of liquid fuel, and investigate the possibilities of refining crude oil into various liquid fuel types. NamCor has refurbished three depots according to international standards, and a fourth is to be set up in Walvis Bay [294]. Fossil oil refining capacity is an idea, but not substantiated by a policy or financial commitments of the government to date. Data on liquid fuel demand and supply is not readily available. Independent production of liquid fuels and national bulk marketing thereof is not regulated in Namibia. To model the techno-economic viability of bio-oil production, South African coal and national liquid fuel price structures will be utilised as comparison. The price structures are presented in Table 5-27.

Table 5-27 Energy price structure for Namibia

Liquid fuel as supplied by various providers; Walvis Bay* Harbour pricing	Rate; average for years 2011-2014 (NAD) [295]
Industrial grade Diesel; wholesale price, ex-Walvis Bay	1157.0 cents l^{-1} (0.05% Sulphur content)
Industrial grade Diesel; wholesale price at Otjiwarongo	1180.9 cents l^{-1} (0.05% Sulphur content)
Export grade coal imported from South Africa, ex-Walvis Bay	714.40 NAD t^{-1}

* in Namibia, the proxy for liquid fuel pricing is Walvis Bay Harbour; the further away from Walvis Bay fuel is delivered, the more expensive it becomes. The price for Otjiwarongo is provided in the table.

5.5.2 Link to other sectors and land use issues

As an indicator for costing of bio-oil and electricity generated using bio-oil, prevailing energy prices serve as baseline. Bio-oil is to be compared to crude oil and industrial-grade Diesel; electricity pricing via the fast pyrolysis routes is to be compared to electricity generated and transmitted via the national grid; the REFITs for electricity pricing as presented in Table 5-26 was used as proxy. Table 5-27 provides an overview of the energy pricing structure currently prevailing in Namibia. As discussed under sections 4.5.1.1 and 4.5.1.2, markets for bio-oil could be established in Namibia, notably to supply liquid fuel to government services providers, like hospitals, correctional institutions (prisons) or boarding schools as source of heat in boilers. The bio-oil could also be used to generate electricity as independent power supplier, both to deliver electricity to the national grid, or supply electricity to a defined community.

5.5.3 Spatial indicators

Otjiwarongo town was of interest to this research due to its strategic location within the national electricity transmission network. “Gerus” is the electricity hub in northern Namibia, located close to Otjiwarongo; several electricity transmission lines are brought together there, and re-distribution transmission lines depart from it. Also, an electricity generation station is installed at “Gerus”. Augmenting electricity generation capacity through fast pyrolysis conversion and connecting to the electricity transmission grid at Otjiwarongo/Gerus was considered to be opportune. Figure 5-10 provides an overview of the national electricity network, with Otjiwarongo/Gerus electricity distribution hub highlighted in the central-northern part of Namibia.

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Figure 5-10 Electricity distribution network of Namibia [291]. The pin indicates the location of Gerus; the circle just below indicates where Otjiwarongo is located. The smaller lines and points indicate the national electricity distribution network (lines = electricity transmission lines; points = substations) in Namibia.

5.5.4 Data sourcing and dynamic features of the data

Consumer prices for energy, i.e. electricity and petrol are regulated. A basic fuel price (BFP) mechanism exists for Diesel and crude oil; this means, the wholesale price level is regulated, ex Walvis Bay harbour, however profit margins of fuel retailers are not. Energy pricing data was obtained from official sources. Electricity prices from the Electricity Control Board (ECB) and liquid fuel prices from NamCor. Electricity prices are those of commercial customers, consuming equal to or more than 33kV (that is, multiples of three-phase power). For Diesel and crude oil, the BFP landed in Walvis Bay harbour were provided. Energy price indicators exclude factors for or costs associated with value added tax, governmental subsidies or taxation based incentives, discount rates or professional fees payable for design, project management, installation, commissioning and training. Included however, are factors for import or export duties and levies. Price indicators are averages of spot prices, and current market prices for the past 24 years used for comparison to bio-oil breakeven prices to be determined. Adjustments to the data are thus not necessary. The techno-economic model (Chapter 8) took account of prices which may change over time mainly due to inflation. Production prices for bio-oil were compared to those of e.g. Europe and USA in Chapter 9.

5.6 MARKET RELATED DATA REQUIREMENTS AND AVAILABILITY – SOUTH AFRICA

5.6.1 Socio-economic, ecological and national policy indicators

The drivers for the use of bioenergy in South Africa are the 2007 Biofuels Strategy [7], the White Paper on Energy [41] and the White Paper on Renewable Energy [40]. The Biofuels Strategy aims to introduce liquid fuels from biomass into the transport fuels market. The White Paper on Renewable Energy incentivises the generation and use of renewable power generation by Renewable Energy Feed-In Tariffs (REFITs), by independent power producers (IPP). The latter goals and REFITs were summarised in Table 5-28.

Table 5-28 Renewable Energy Goals for South Africa

Type of Energy; description of goal	Penetration rate, nationally; operational framework Integrated Energy Plan (IEP):	Approved REFIT [296]
Liquid Biofuels, based on e.g. first and second generation biofuels; implemented since 2009	2% overall; or at least 400Ml/annum	Fuel cost: ZAR30/10^6BTU Heat rate: 15,750BTU/kWh
Power generation; based on supporting independent power producers with a REFIT; support since 2009 on a tender basis. The target should total 10,000 GWH; implementation is monitored by National Electricity Regulator of South Africa (NERSA)	**Phase I - 2009 – 2013:** build capacity of >1MW, each; based on wind, concentrated solar, land-fill gas and small hydro plant. On average, each IPP built has 1.1MW installed. By 2013, 13MW each, should have come from biomass and biogas; targets were not attained.	Not applicable; energy from biomass was not part of Phase I.
	Phase II - 2013-2018: grid connection for IPP producing power >1MW; focus on large-scale grid connected photovoltaic systems (>1 MW), biomass solids conversion (13MW in total), biogas (13MW in total) and concentrated solar power (CSP) with 6 hours per day storage.	REFITs for electricity generation plants based on biomass with an installed capacity will be reimbursed with a levelled cost of production of ZAR1.18/kWh. Assumed load factor: 80%

5.6.2 Link to other sectors and land use issues

Sourcing input materials for fast pyrolysis is strongly linked to the agricultural sector. The South Africa Biofuels Strategy [7] and the IPAP 2014-2016 [289] also link biomass renewable energies to the agricultural sector. However, there is a difference between bio-oil from fast pyrolysis and bio-ethanol or bio-diesel bio-gas as suggested by South African authorities. Bio-oil production was not be based on agricultural input materials like maize, soya bean or sorghum; but was based on wood from 'problem' species. There is therefore no likelihood that bio-oil production would compete with food security or caused deforestation (section 1.1 and 2.3). In addition, feedstock for bio-oil production would be sourced from within South Africa; meaning that feedstock sourcing is not dependent on imports or the outflow of foreign exchange to source feedstock, thus feedstock import price fluctuations are curbed. Prices for bio-oil and electricity generated from wood-based biomass can be kept stable as these can be directly controlled by continuously monitoring and evaluating the production process, including sourcing of feedstock.

5.6.3 Spatial indicators

Marketing and distribution of bio-oil and electricity would be carried out in the South African regions/provinces where sourcing of feedstock and production of fast pyrolysis energy types takes place, i.e. Eastern and Western Cape, Limpopo, Mpumulanga and Northwest Provinces. The latter provinces are inhabited by a large percentage of rural communities and providing these with energy fulfils another South African macro-economic development goal [30, 40, 41]; stimulating socio-economic development; providing access to affordable energy; and creating jobs in rural areas (section 1.1).

The distribution of bioenergy from fast pyrolysis is dependent on grid access points offered to independent power producer and generators. These are presented on a map prepared by the national electricity company (Eskom Ltd) [297] in Figure 5-11. The existing 'renewables' and 'future renewables' power generation stations operated by Eskom are located in Western Cape Province (Klipheuwel); and Northern Cape (Upington); based on concentrated solar power. Eskom is not proposing wood-based power generation; however, grid access points for electricity generated via the fast pyrolysis would likely be available at the power stations or distribution substations on the grid. Individual agreements with Eskom Ltd would need to be concluded prior to the commencement of a project based on the policy guidelines presented by the South African government [40, 41].

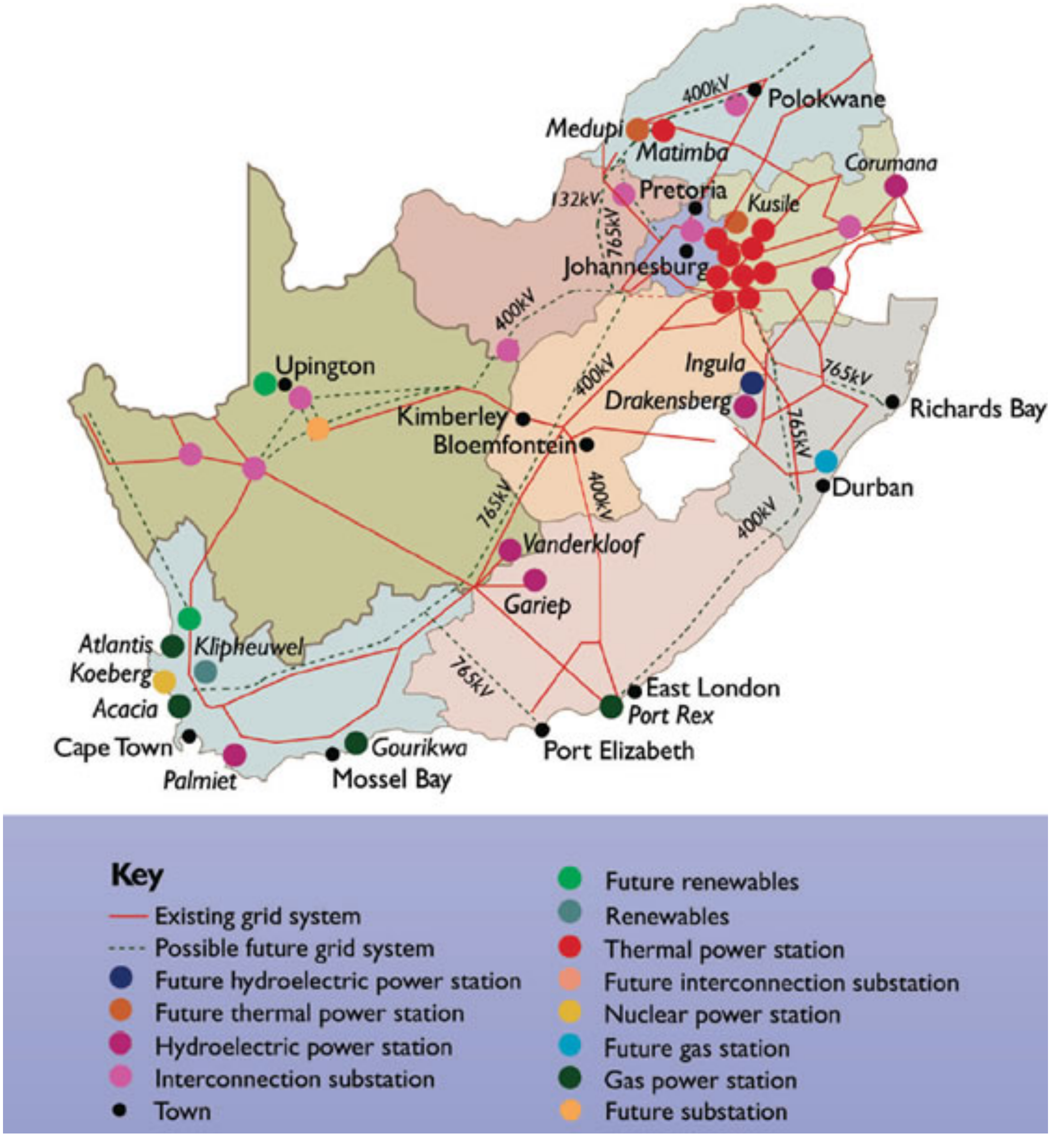

Figure 5-11 **South African electricity grid network; the map indicates the various grid access points for electricity generated from the various types of resources [297]**

5.6.4 Data sourcing and dynamic features of the data

Data related to South African markets for bioenergy was sourced from governmental agencies. The data was presented as policy indicators valid over a certain period; in this case for the period 2013 - 2018. No adjustments to the data are required.

6 BIOMASS RESOURCES MODELLING

In this chapter biomass resources modelling is discussed, based on data made available in Chapter 5. In the Namibian case, wood-based biomass resource modelling for the farmland districts of Okakarara and Otjiwarongo was carried out. The species predominantly available for fast pyrolysis is *Acacia mellifera* sp. *detines*. In the South African case, two wood-based biomass types were considered for resource modelling, located at three different sites. These relate to woodlands and bush encroachment, growing in the Limpopo, Mpumulanga and Northwest Provinces; and alien plant species growing in the Eastern and Western Cape. The wood species investigated are mainly indigenous and alien *Acacia* types, and to a lesser extent *Eucalyptus* types.

Modelling of the biomass resources was informed by data obtained through the literature review presented in Chapter 4. The distribution of the wood-based biomass resources and data relevant to modelling in both, Namibia and South Africa, were discussed in Chapter 5. Biomass characteristics in relation to fast pyrolysis conversion are discussed in Chapter 7. By modelling biomass resources, the aim of this Chapter is to:

- determine the long-term wood-based biomass growth rate
- determine the sustainable use of these wood-based resources for fast pyrolysis over the long term;
- record changes in agricultural land productivity when wood-based biomass resources are used in the identified Namibian areas;
- highlight biodiversity changes in the respective South African provinces; and
- determine the duration within which the above substantial biodiversity changes could occur.

6.1 BIOMASS RESOURCES MODELLING - NAMIBIA

This section provides a modelling framework for wood-based biomass resources in Namibia that can be used in fast pyrolysis conversion to produce bioenergy. Two model frameworks are discussed (Model 1 and Model 2); however only one model was subsequently used for bioenergy modelling.

Bush growth is influenced by a combination of factors such as soil type, availability of ground water, altitude, latitude, precipitation, i.e. rainfall, temperature or seasonality, competition with other species, i.e. flora and fauna (e.g. livestock), for the same resources; as well as land management principles adopted. In the literature review, no reference could be found to work done on the degree of correlation between any of these factors individually or in combination. In fact, because of the growth patterns of bush species, which would take multiple years to reach maturity, it is likely that a cause-effect correlation between one-off events in one year, and encroachment, could be difficult to demonstrate. Data outlined in Table 5-1 and Table 5-12 certainly suggest there was no direct correlation between policy and farm management, and changes in bush growth/spread (where land management refers to interventions by land owners and/or policy directives for agricultural land use).

The only historic data available in the literature related to bush encroachment, was regarding the extent of bush encroached areas (

Table 5-7). There was no comparable data available on bush biomass, or tree equivalent units. Therefore in further calculations, bush encroached areas has been taken as a proxy for bush biomass growth, accepting that bush spread would not capture possible increases in density in already bush encroached areas, and is therefore a "conservative" estimate of biomass growth. Based on information available, the parameters that were tested for correlation were time, rainfall and livestock stocking rates.

In Figure 6-1, rate of increase between consecutive measures was plotted against bush coverage, to check for patterns. No significant correlation could be found (R^2 = 0.6088), although it would appear that the rate decreases as the area covered increases. Equally, no apparent correlation could be found when plotting the rate of increases between consecutive measures against rainfall (as provided in Table 5-1). The rainfall data series (1891-2013) are stationary and can therefore be used for modelling without adjustment.

From

Table 5-7, the computed weighted average spread of bush encroachment since 1957 was calculated as 4.35% per annum. However, having applied this growth rate to reconstitute bush coverage expansion for the period 1957 to 2013 resulted in far greater bush coverage than reported (the total area demarcated for livestock would have been bush encroached with an area of 51.6Mha in 2014). It thus seems that even reported data causes problems, mainly because of outliers (Figure 6-1).

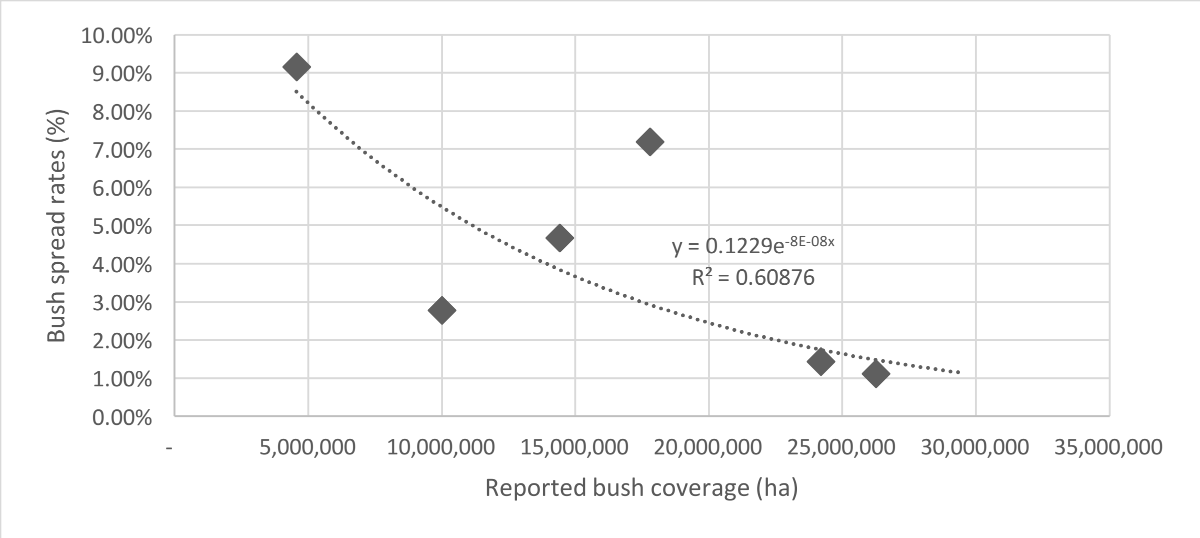

Figure 6-1 Plotting the perceived relationship between bush spread rates (%) between reporting periods against reported bush coverage (ha)

When reported bush coverage was plotted against bush expansion rates for the same period 1957 to 2013, a linear growth trend could be established for bush coverage. This suggests that there is not a constant rate of increase that can be applied, but rather bush spread along a linear trend would need to be used to predict future bush spread patterns (Figure 6-2); the reliability of the trendline was given as R^2=0.9604.

Equation 6-1 Regression formula derived from linear trend for bush coverage

$$y = 466961x - 910148554.23$$

Where:

x is the specific year in which bush coverage is to be predicted; and

y is the predicted bush spread in %.

Applying Equation 6-1 to the initial (1957) value resulted in bush coverage of 29,843,939ha by 2013. Although the simulated bush coverage amount differs by 364,660ha from the measured area, this difference constitutes a difference of only 1.2%. In addition, the linear regression formula seems more reliable to use as tool to predict future bush expansion than applying the weighted average bush coverage growth rate of 4.35%.

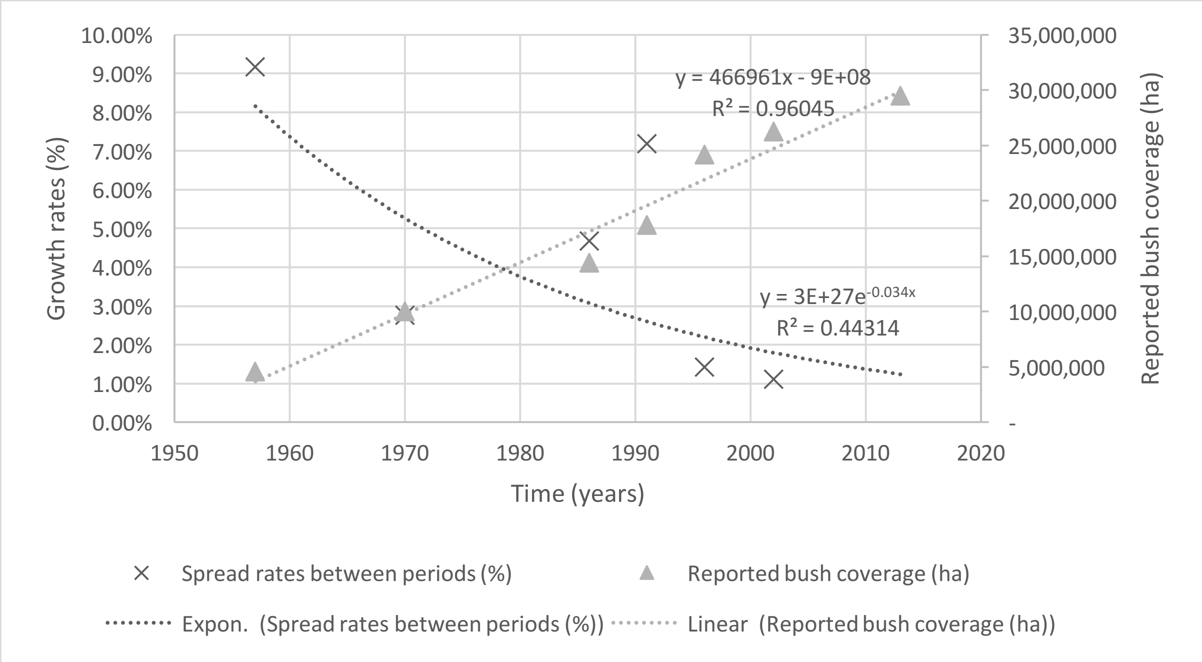

Figure 6-2 **Plotting the perceived relationship between bush spread rates (%) between reporting periods against reported bush coverage (ha)**

Nonetheless, even the simulated expansion rate and trend poses a challenge to predicting future bush coverage, and wood inventory. The spread rate slowed exponentially over the period 1957 to 2013, leading to a situation of uncertainty which average growth rate to apply to bush population increase. The matter is furthermore complicated as it is expected, that once bush is cleared, the expansion rate may be accelerated, similar to a situation for the period 1957 to 1986. To account for this possible accelerated growth of bush, a spatial bush expansion rate of 3.18% (Figure 6-3) (which is the average of the simulated growth rates based on the linear regression formula) was assumed. This expansion rate is taken as a proxy to indicate the bush population growth rate, and thus wood-based biomass growth.

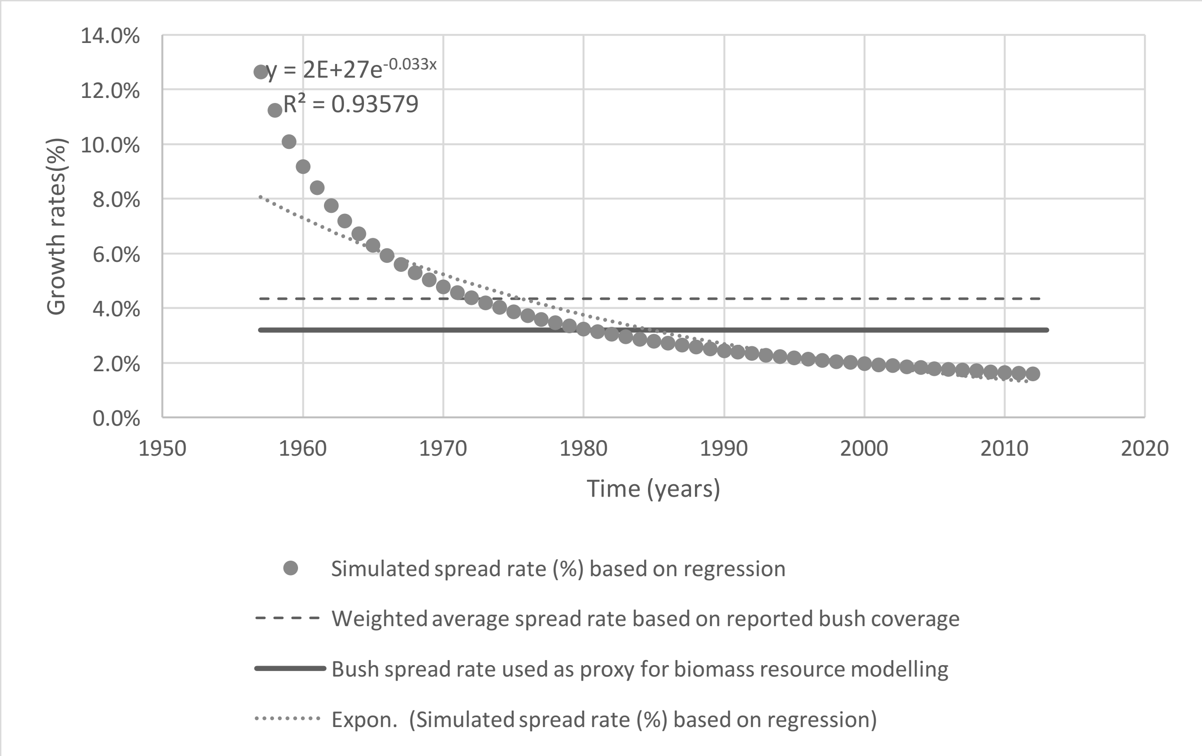

Figure 6-3 **Various bush growth rates (%): established weighted average growth rate for the period 1957 to 2013; the simulated growth rate based on Equation 6-1, and the growth rate used for wood-based biomass modelling**

Using the bush growth rate of 3.18% without harvesting interventions in future, resulted in the prediction that all livestock production areas of 51.7Mha would be covered by bush in approximately 2035. This suggests the need to extract bush, thus presenting a possibility for improved livestock production output.

Figure 6-4 presents rainfall, livestock stocking and bush coverage graphically for the period 1957 to 2013. An Analysis of Variance (ANOVA) using EViews®8 to analyse the relationship between these three parameters (with bush coverage as the dependant variable) resulted in very low reliability of this relationship ($R^2 = 0.2897$). It was therefore concluded that bush growth over time occurs regardless of rainfall and livestock stocking rate.

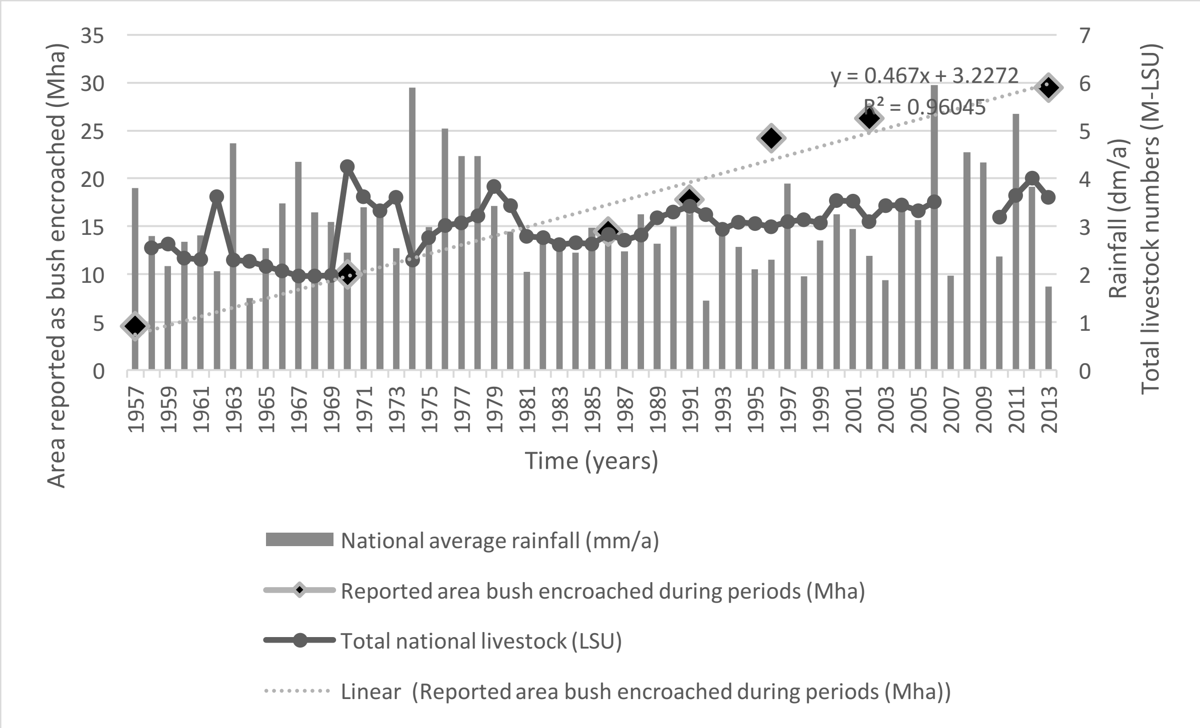

Figure 6-4 Plotting the perceived relationship between bush growth rates (%) between reporting periods against reported bush coverage (ha)

For modelling purposes the bush growth rate of 3.18% was used to model biomass for Okakarara and Otjiwarongo farmland areas. The approach seems simplistic (as e.g. climatic conditions, including atmospheric CO_2–levels [298, 299], policy and regulatory as well as farming practices may influence bush inventory levels over time); however with exact data lacking for all factors influencing bush growth and/or bush inventory data, it was considered a plausible approach. The aim with this approach was to arrive at a bush growth rate to determine the quantity of wood-based biomass that could be available in future for fast pyrolysis. The aim was not to establish an irrefutable bush inventory and growth model.

6.1.1 Wood-based biomass from Okakarara and Otjiwarongo farmland areas

Based on a bush growth rate of 3.18% annually as well as the established bush inventory (2013 data) the future bush inventory of Okakarara and Otjiwarongo could be computed. It was assumed as only a weak correlation between bush, livestock and rainfall exists at national level, similar would be true at regional level. In addition, neither historic bush inventory nor spread in the districts of Okakarara and Otjiwarongo were available. It should be noted that the complete area of Okakarara and Otjiwarongo are already bush encroached; thus bush density is expected to increase, and with that relative wood yield. Over the 20-year bush in Okakarara district, composing of *Acacia mellifera* sp. *detines* and *Dichostachrys cinerea*, would have accumulated a total wood-based biomass of some 57.39Mt. Over the same period, composing of *Acacia mellifera* sp. *detines, Acacia reficiens* and *Colospherma mopane*, bush in the Otjiwarongo district would have accumulated some 167.43Mt of wood-based biomass. Predicted bush inventories for these farmland areas are provided in Table 6-1.

The bush inventory is given in Mt as modelling biomass availability for fast pyrolysis is easier done on a weight basis; TE-units is not practical for techno-economic modelling.

Table 6-1 Predicted total bush inventory for the Okakarara and Otjiwarongo farmland areas, measured in Million-tonnes (rounded Mt) respectively, if no harvesting interventions are undertaken for the period 2013 to 2033

Observation (corresponding to a period)	Okakarara	Otjiwarongo
2013 (year of assessment)	65.83	192.03
2014	67.93	198.15
2015	70.09	204.46
2016	72.32	210.97
2017	74.62	217.69
2018	77.00	244.62
2019	79.45	231.77
2020	81.98	239.15
2021	84.59	246.77
2022	87.28	254.62
2023	90.06	262.73
2024	92.23	271.10
2025	95.89	279.73
2026	98.94	288.64
2027	102.10	297.83
2028	105.35	307.31
2029	108.70	317.10
2030	112.16	327.20
2031	115.73	337.61
2032	119.42	348.37
2033	123.22	359.46

6.1.2 Modelling wood-based biomass utilisation for Okakarara and Otjiwarongo farmland areas

As presented in Table 5-9 and Table 5-11, the Okakarara and Otjiwarongo farmland areas are completely bush encroached and carrying capacity is said to have decreased. This means that bush cannot spread further in terms of land coverage; it would only become denser in these specific areas, or spread to adjacent district areas if that area is less densely populated or if no wood-based biomass is extracted. With bush encroachment becoming denser, the area becomes more and more crowded, competing for the same resources; consequently carrying capacity is assumed to drop further. Assumptions made when modelling how much wood-based biomass can be extracted from the Okakarara and Otjiwarongo farmland areas and thereby improving carrying capacity are presented in Table 6-2. A simplified conceptual and mathematical model is assumed: for the first model (Model 1) the annual rate of harvesting / extraction of bush is greater than the bush population growth rate, expressed in %. The model is solved in a spreadsheet approach (section 4.4.1). The proposed harvesting schedule as presented in Table 5-4 was used, both for Model 1 and 2 extraction of biomass. The extraction models determined the area of farmland to be cleared annually; the harvesting schedule determined what type of harvesting (or aftercare) is to be undertaken as well as the possible biomass yield from such harvesting.

Proposing the two models for biomass extraction has the purpose to determine the sustainability of bush harvesting over the long-term, i.e. beyond 2033. Model 1 proposed biomass extraction on an annual percentage bush harvesting rate (% of standing density in wet-tha^{-1}). Model 2 proposed biomass extraction on a specific area being cleared annually (ha being cleared annually, per farm).

Table 6-2 Assumptions underlying bush encroachment modelling for biomass in the Okakarara and Otjiwarongo farmland areas

	Okakarara	Otjiwarongo
Desired level of bush density (TE ha^{-1})	2,500	2,500
Aspired carrying capacity (CC) (level as in 1970) (kg ha^{-1})	45.00	42.24
Annual bush growth rate (%)	3.18	3.18
Potential yield (wet-t/ha) in 2013	45.55	60.19
Model 1: percentage annual bush extraction rate (% of standing density in wet-tha^{-1})	5	5
Model 2: area based annual bush extraction rate (ha being cleared annually, per farm)	500	500
Grazing capacity increase for the areas treated (annual)	doubles	doubles
Duration for which biomass is modelled (years)	20	20
Total potentially available wood-based biomass at first time harvest (Mt) in 2013	65.83	192.03

Taking the suggested harvesting cycle (Table 5-4) into consideration, it is assumed that the full rangeland potential is only achieved after 20 years or longer of the first bush harvesting intervention on a certain site. This means that the areas first harvested will only be fully recovered; likely with the aspired carrying capacity after 20 years. Considering Model 1 (Table 6-2), for example over the 20-year period and extracting 5% wood-based biomass from the farmland areas 1.855Mha would have been cleared of the Okakarara farmland area ; and of that 609.7kha would likely have been fully rehabilitated if the harvesting and aftercare cycle is followed as suggested. For the Otjiwarongo farmland area 4.1Mha would have been cleared; and of that only 1.35Mha would have been fully rehabilitated. The results of modelling biomass resource use at a level of extracting 5% of it, are summarised in Table 6-3 and Table 6-6.

Table 6-3 Results of bush encroachment modelling for biomass in the Okakarara and Otjiwarongo farmland areas, assuming a 5% extraction rate, after a 20-year cycle (Model 1)

	Okakarara	Otjiwarongo
Total district area (2013) (Mha)	1.45	3.19
Approximate average area of farmland cleared annually (Mha)	0.24	0.20
Total area cleared over a 20-year cycle (Mha)	1.86	4.10
Approximate potential bush yield remaining (wet-tha^{-1})	26.33	34.80
Average amount of wood extracted annually (Mwet-t)	2.83	8.25
Total farmland area gain (Mha)	0.61	1.35
Adjusted average annual bush (re-) growth rate (%)	1.17	1.17

The farmland area to be cleared annually in the Otjiwarongo district is less than in Okakarara because the original potential yield (wet-t/ha) in the former area is higher. The cumulative area cleared is greater in both cases because the harvesting cycle foresees harvesting at the same site at multiple times. The rate of re-growth of bush would slow to 1.17% per annum in both cases, because the rate of extraction of wood at 5% is greater than the original increment of bush inventory at 3.18%.

Table 6-4 Results of bush encroachment modelling for biomass in the Okakarara and Otjiwarongo farmland areas, assuming bush will be harvested annually from 500ha from each registered farm over a 20-year period (Model 2)

	Okakarara	Otjiwarongo
Total district area (2013) (Mha)	1.45	3.19
Approximate average area of farmland cleared annually (Mha)	0.067	0.81
Total area cleared over a 20-year cycle (Mha)	1.35	16.28
Approximate potential bush yield remaining (wet-tha^{-1})	31.17	43.60
Average amount of wood extracted annually (Mwet-t)	1.70	27.12
Total farmland area gain (Mha)	0.46	5.50
Adjusted average annual bush (re-) growth rate (%)	1.17	1.17

Model 2 suggests that in the case of Otjiwarongo more farmland would be gained than the demarcated area for that district. The main reason may be that although 603 land titles are registered for the district, these are not all either on average 5,000ha large; or not all registered titles are exclusively used as farmland, but also other purposes; or a combination to the latter factors. This suggests that initial harvesting of wood in the Otjiwarongo district at a constant rate could be reduced and still be effective to improve rangeland improvements. Alternatively, less land titles could be cleared over the period.

6.1.3 Conclusions on wood biomass resources in Namibia

Table 6-3 indicates that at a 5% harvesting level also considering the harvesting cycles presented in Table 5-4, wood-based biomass would be available for approximately another 180 years in the Okakarara, and 240 years in the Otjiwarongo district respectively.

Model 1 (total area weight-based biomass extraction) is not very useful in the Namibian socio-economic context. Farmers prefer to use an area-based clearing factor; this would give them a clearer indication of the costs for clearing and logistics to make wood available to a fast pyrolysis conversion plant; and possible rangeland improvements annually. Farmers are not subsidised or assisted in any way to clear bush; all expenditure in this regard has to necessarily be covered by the cash-flow available to the farmer. It may therefore be that the farmer would not clear any bush in a given year due to cash-flow constraints. The latter happens typically during drought years or when livestock farming activities slack.

To sustain the supply of wood-based biomass to fast pyrolysis a two-pronged approach may be considered to entice farmers to clear bush for commercial purposes:

- follow the biomass supply model of the cement factory [112] (section 4.1.2). While farmers would have to pay to have their land cleared, they wouldn't have to own harvesting or logistics equipment to extract wood to supply such biomass to a fast pyrolysis plant.
- offer to off-take wood-based biomass. In this way farmers may want to procure the necessary equipment to deliver biomass to a fast pyrolysis plant and may therefore be able to sustain a living by bush utilisation.

The latter mentioned approach was followed to model supply of wood-based biomass to fast pyrolysis (Chapter 8).

Extracting wood using Model 1 seems to show desired results much faster, but may also be more expensive. Therefore Model 2 was used to determine the amount of wood-based material available for bio-energy generation via fast pyrolysis. The model was integrated into the techno-economic model and solved in a spreadsheet approach. It was assumed that the average farm size in the Okakarara and Otjiwarongo farmland areas is 5kha. Model 2 (Table 6-2) suggest that some 500ha per year are considered to be cleared at certain intervals (Table 5-4) as per 20-year harvesting cycle. This means, annually some 10% of the land is cleared per farm per year. The difference between Model 1 and 2 is however, that on-farm clearing happens in a decentralised manner and reliance on wood-based feedstock delivery by the farmer to the fast pyrolysis plant is high. Flexibility of feedstock supply can be implemented. If a farmer decides to deliver more feedstock at certain point in time, the fast pyrolysis plant operation management could accommodate that. If less feedstock is delivered, another farmer's surplus delivery could cater for shortfalls (section 8.3).

6.2 BIOMASS RESOURCES MODELLING - SOUTH AFRICA

This section provides a modelling framework for wood-based biomass resources in South Africa that can be used in fast pyrolysis conversion to produce bioenergy. Focused attention will be on geographic areas which show the highest potential yield for harvesting biomass sustainably and which can be converted via pyrolysis to maximise the returns to communities living in those areas as laid out in the Integrated Energy Plan [300] (see also Chapter 2) and the National Forestry Act [124]. The geographic areas previously identified for bio-energy production are Eastern and Western Cape, Limpopo, Mpumulanga and Northwest Provinces. The wood species investigated are mainly indigenous and alien *Acacia* types, and to a lesser extent *Eucalyptus* types.

6.2.1 Modelling of wood-based biomass resources in South Africa

The available wood-based biomass resources for fast pyrolysis in South Africa can be computed by adding up mean annual residual wood-based biomass values per resource. This seems to be a simplistic approach, but each resource's potential has to be quantified first. Wood-based biomass resource data was available in South Africa as industries generating and/or requiring this type of resource are regulated. To establish the quantity of wood available from bush encroachment, land cover (Table 4-2) was used as proxy, with densities determined as described in 4.1.4. The amount of wood available from eradication of invasive alien wooded plant species on an annual basis is a result of the interventions carried out by the 'Working for Water' programme; described in section 4.1.5. Details follow with descriptions of each type of wood-based biomass resource below. The general model describing available wood biomass resources in South Africa is expressed by Equation 6-2.

Equation 6-2 Total wood-based biomass resources available for thermo-chemical processing in South Africa

$$\sum_{j=1}^{n} (\boldsymbol{\delta\beta})\mathbf{x}_j\,(\boldsymbol{\alpha}_j + \mathbf{1})$$

The first objective function of Equation 6-2 is to maximise total net resources available for pyrolysis processing at any certain point in time.

Where:

α_j is the resource production factor (resource harvesting rate) coefficient for a specific resource x_j;

j = is the type of wood-based biomass resource, like forest residues, woodland biomass, thicket biomass, shrub land biomass, aliens/bush encroachment biomass, plantation wood (round wood, plantation residue, silvicultural residue), agricultural residues/waste and processing residues.

Coefficient α_j is the resource accumulation or harvesting rate depending on the resource analysed, i.e. forest resource or aliens/bush encroachment eradication.

Coefficients δ and β are the size of the feedstock available to thermal processing, i.e. δ diameter or width, and β length, both in mm.

Based on various research findings by Ward [160], Eamus and Palmer [161]; Von Malitz and Scholes [156]; governmental projects [155, 158] and Shackleton [159], naturally grown resources have a growth rate of 2.5% per annum. In addition, naturally grown biomass accumulation is assumed to be limited and remains within the boundaries of land cover and use classification of South Africa as provided by Table 4-2.

α_j for commercially grown biomass resources is based on past resource production data and consequential by-products that have not been utilised. Past inventories, as indicated by data, for certain resource types may still be available (e.g. saw dust in saw mills). However, the literature review (section 4.1.3.2) has shown that no inventory with commercial viability is available.

The following sections discuss the models for each residual wood-based biomass resource available for bioenergy via fast pyrolysis in South Africa in more detail. The residual wood-based biomass resources are from commercial forestry industry (section 4.1.3.2); bush encroachment and alien invasive wood-based plant species eradicated through the 'Working for Water' programme.

6.2.2 Modelling of commercial forest biomass resource available for conversion to bioenergy

Coupled with the findings (section 4.1.3.2) on sales of wood chips and mill residues for the pulp and paper industry, and firewood and the production of charcoal [142], only a negligible amount of usable wood residue is available for fast pyrolysis conversion in South Africa. From analysis of resources from commercial forest plantations and their registered uses (section 4.1.3.2), a certain amount of residue is available for other purposes, but are declining. From data sets analysed, the firewood and charcoal production industries have increased the utilisation of this resource (Figure 4-4). Regulatory measures further influence the availability of this resource in South Africa. The total amount of commercial forestry residues nationally are spread across

South Africa, i.e. in those provinces where forestry plantations and primary processing plants are situated, over some 1.3Mha. The transport and logistical arrangements to collect and store this resource would be cumbersome if thermo-chemical conversion does not take place in close proximity of the biomass resource. Planning for security of supply of this resource is uncertain. Scope to add additional pyrolysis conversion systems in South Africa seems limited. This option was not pursued any further.

6.2.3 Modelling of available biomass resources from bush encroachment

Woodlands and forests will remain a key source of biomass to individuals and communities which they will utilise as part of their livelihood (section 4.1.4). Poverty is another key driver concerning utilisation of forest resources in South Africa. Woodlands and natural forests will remain under pressure due to large population groups' continued reliance on wood for energy. Some woodlands may become depleted while others may become inaccessible due to bush encroachment. Security of wood-resource supply for bio-energy production as suggested under this research considered that energy should first be supplied to rural and poor communities, before wood/forest biomass could be considered for fast pyrolysis conversion.

Various persons (section 5.2.1) have compiled data on bush encroachment species, but without providing sufficient detail on inventories prevalent in the affected areas. The data found suggests that biomass available pertains to woody plant canopy cover above 50%, apparently irrespective of their height and diameter, or possible total biomass available for industrial use per hectare. Assessments done (section 154), on how to sustainably utilise biomass from bush encroachment in Namibia deliver an example for modelling biomass resources under South African conditions. The focus for biomass resource modelling from bush encroachment in South Africa is thus also relating to *Acacia* types.

Research of dynamics on bush encroachment in woodlands suggests that trees and shrubs populations spread at rate of 2.5% per annum, computed as 4% growth minus 1.5-2% natural dieback (section 4.1.4). Wood-based resources from woodlands where bush encroachment occurs are considered to be spread over an area of 29Mha (Table 4-3) but specifically affect 19.3Mha within the woodlands areas [148]. The total woodlands inventory was assumed to be 28.5Mt of harvestable wood in 2011 [161]. If no other harvesting, apart from community's use, takes place, the woodlands harvestable wood inventory would have grown to a total of 45.48Mt after 20 years. To render the areas affected by bush encroachment agriculturally productive again, it is required that the mean annual increment and part of the standing inventory of the bush is harvested. A bush harvest and aftercare cycle similar to that used in Namibia (Table 5-4) was considered also for South Africa. This is also in conformity to best regional practice and experience from research done in other Sub-Saharan countries, notably Namibia and Kenya [96, 106, 265, 301].

The underlying principles to model the use of available feedstock from bush encroachment in South Africa followed arguments as those used for Namibia. The following commercial harvest activities, bearing land ownership of woodlands in mind (section 4.1.4), based on *a priori* annual wood mass yields as proposed by Ward [160], are achievable in identified bush encroached areas:

- Only woodlands with canopy cover of over 50% were taken into consideration. Woodland areas with less than 50% canopy cover were assumed not to be bush encroached, and the yields from these areas were assumed to be too low to warrant commercial harvesting activities.
- Areas with a canopy cover over 50% were assumed to span over an area of 19.3Mha [148] and an average possible yield of 11.67t/ha, as computed using Eamus and Palmer's assessment [161].
- To prevent further bush encroachment, follow up harvest are suggested to be carried out on a cyclical basis as in the Namibian case (Table 5-4).
- This is accounted for in the model.

Bush encroachment in woodlands, if harvested or cleared cost-effectively, provides biomass for bioenergy which could otherwise not be used. The economic viability of this resource depends on securing guaranteed supply contracts based on the relatively broad dispersion of the resource over a large area and ownership of the resource (sections 2.1, 4.1.3.1 and 4.1.4; Table 4-3). How land ownership was taken into consideration for techno-economic modelling is discussed further under section 8.6.

6.2.4 Modelling of wood-based biomass resources available from alien invasive plant species

In 1995 Marrison and Larson analysed the biomass energy production potential for Africa by 2025 [302]. Caveats of the projections were identified by the authors. Nonetheless, under South African legislative conditions, the authors suggestions that additional *Eucalyptus* plantations could be established on 'not forest, not wilderness and not cropland' to satisfy future bioenergy needs, were considered as not feasible: especially as planting of *Eucalyptus* for commercial purposes is strictly regulated in South Africa. No radical change to the policies of South Africa is expected, considering that the Government of South Africa actually spends billions of Rand annually to eradicate alien invasive plant species, including *Eucalyptus* in areas outside commercial forestry plantations (section 4.1.5 and 6.2.4.).

Assessments done through the Working for Water (WfW) Programme [152] on alien invader woody plants suggest that various plant species are available for industrial utilisation. Alien grass species have also been identified as potential energy sources [303, 149]. However, detailed inventory data is lacking. Figure 6-5 illustrates the geographic distribution of invasive alien plant species, highlighting the degree of invasion. This research will concentrated on inventory assessments of alien plant species in the Eastern and Western Cape as done by Theron [304].

Aston University

Illustration removed for copyright restrictions

Figure 6-5 Geographical distribution of invasive alien plant species in South Africa [303]

In general, the WfW Programme is commended by the South African Government for its efforts to align and harmonise the core objectives. In particular though, the programme is facing impediments to success, not at its central management level, but rather at satellite projects' implementation level, which can be summarised as follows [174]: lack of production capacity, limited financial resources, lack of marketing skills, poor marketing tools, difficulties with accurate costing, issues of distance and isolation, transport and distribution and (possibly) a lack of capacity for on-going market driven product development and design [175]. It was recommended that alternative technologies and approach to the utilisation of wood material as a feedstock are to be taken into consideration. This would include thermo-chemical conversion technology which is both environmentally friendly and feasible.

As the aim of the WfW programme is to eradicate alien plant species in South Africa; this resource will decline over time. Based on the already treated areas and the inventory assessments carried out on *Acacia mearnsii* (section 4.1.5), it was assumed that a fixed amount of area would need to be cleared from alien invasive wood-based plant species on an annual basis; human and financial resources of the South African Government permitting. Over time, the yield from initial clearings should decline, but follow-up clearing would need to continue until all alien plant species in categories 1 and 2 would have been cleared. Taking these factors and data availed by the WfW programme into consideration, Equation 6-3 was derived. The regression was derived from data on clearings for the period 1995 to 2008.

Equation 6-3 **Regression trendline based on clearing alien invasive plant species in South Africa between 1995 and 2008, based on** Error! Reference source not found.

$$y = WfW_{wood} = 0.5505x - 1093.9$$

Where:

x = time (year) in which clearings took place

$y = WfW_{wood}$, is the wood-based biomass availed after clearings (in tonnes).

Interpreting the regression output components of Equation 6-3, an R-squared of 0.6507 indicates that this regression is not significant in predicting the amount of biomass that would be available after clearing of alien invasive plant species. Even if consideration would be given on how much residual biomass would be left after other uses of such biomass has taken, the situation would not change to the positive. It was thus considered less useful to base biomass resource modelling for fast pyrolysis on the actual amount of biomass cleared for the period the WfW programme has published the data. Figure 6-6 visualises how much wood was yielded after clearings.

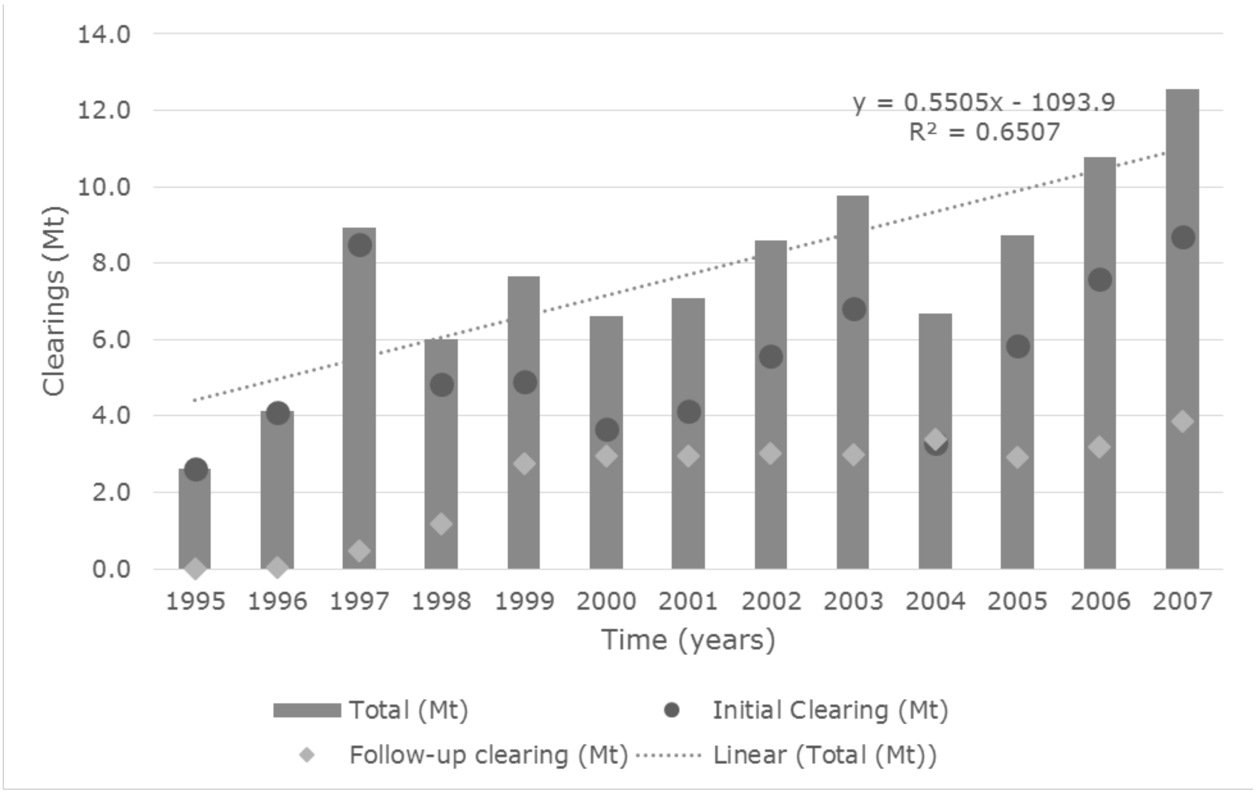

Figure 6-6 Wood based biomass from clearing of alien invasive plant species in South Africa

There also seems to be no relation between the area cleared from alien species and the yield of wood based biomass, i.e. no cointegration (Figure 6-7). The R-squared for this regression trendline is rather low at 0.5754. One reason may be that a complete biomass potential assessment was not done, and published data from the WfW programme span over a limited time horizon.

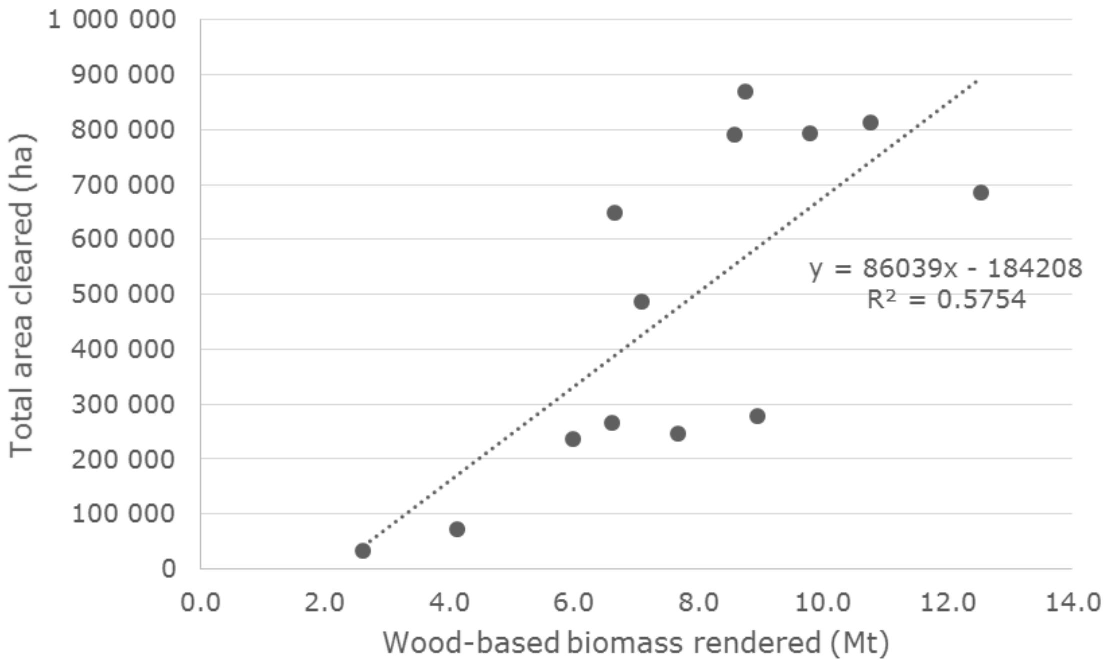

Figure 6-7 **The relation between area cleared and amount of wood-based biomass yielded from clearing invasive alien plant species in South Africa**

In the Eastern Cape, alien plant species are cleared at an average rate of 17,950ha per annum; and in the Western Cape at an average rate of 37,401ha per annum for initial clearing [176]. The clearing and follow-up clearings are pre-dominantly done mechanically, and aftercare is done by arboricides' application. However, arboricides' application does not deliver any additional wood-based biomass as feedstock for bioenergy production. Table 6-5 summarises the wood-based biomass potentially still available for bioenergy production via fast pyrolysis, considering also wood that is already utilised elsewhere as published by the WfW programme.

Table 6-5 **The potential wood yield derived for bioenergy production from alien invasive plant species in the Eastern and Western Cape, South Africa [173, 174, 175, 176, 178]**

	Eastern Cape	Western Cape
Area still left to be cleared (Mha)	0.35	3.05
Average area cleared annually (ha)	17,950	37,401
Wood production at initial clearing (t/ha)	70	111

6.3 CONCLUSIONS ON ESTIMATED BIOMASS POTENTIAL IN NAMIBIA AND SOUTH AFRICA

The potential of wood-based biomass resources in Namibia and South Africa seems substantial. The establishment of how much wood-based biomass resources would be available was however challenging in terms of current and future production inventory and yield levels, both from predominantly bush encroachment and invasive alien plants. Modelling wood-based biomass resources available for bioenergy, under the uncertain circumstances of inventory and yield levels as discussed in this chapter, was achieved by analysing panel data obtained from various sources and presented in Chapter 5.

In contrast to fossil fuels, the use of biomass for energy provides significant environmental advantages. Plant growth needed to generate biomass feedstock removes atmospheric carbon dioxide, which offsets the increase in atmospheric CO_2 (carbon dioxide) that results from fossil fuel combustion. Pyrolysis is the main way for sequestrating carbon in char which could be returned to the soil [76] if not utilised as process energy; thus a way to offset CO_2 added to the atmosphere that results from fossil fuel combustion. The climate change effects of CO_2 from fossil fuels are now generally recognised as a potentially serious environmental problem. To meet the goals of the Kyoto Protocol Agreement, Namibia and South Africa are not obliged to reduce greenhouse gas (GHG) to a level below the 1990 emissions in 2012. However, Namibia and South Africa face immense shortages of energy. Energy shortages can also be mitigated by using alternative technologies, by using fast pyrolysis, to produce energy and reduce GHG emissions. Carbon dioxide increases concentration of GHGs. The combustion of fossil fuels accounts for two-thirds of global anthropogenic CO_2 emissions, with the balance attributed to land use change [240].

Wood-based biomass sources can be converted to bioenergy and would be a reasonable choice to replace fossil oil. By deriving more energy from renewable biomass feedstock like agricultural and forestry residues, encroachment and alien bush or trees species, Namibia and South Africa may fulfil the earlier described 2013 and 2016-goal of augmenting energy supply (power and biofuels) by biomass derived fuels without depriving rural communities of wood for their source of energy[305, 306]. Wood is the single-largest renewable energy source currently being used in South Africa (some 8% of the 11% renewable energy sources), surpassing solar and wind power as an energy source [307].

It is expected that bioenergy from wood-based biomass can cover some of the energy needs in both Namibia and South Africa. In the Namibian case, especially the capacity to generate additional, i.e. on-grid and off-grid, electricity in the country itself is of importance (sections 1.3.2 and 2.4). Namibia's existing electricity needs are around 610 MW with an annual increase of 3%. New projects to generate additional electricity of 152 MW in Namibia are planned between 2012 and 2016. It is expected that using Namibia's bush encroachment via fast pyrolysis, electricity amounting to at least 20MW could be produced (Chapter 9).

In the South African case, annual existing electricity demand is above 36,000MW. Additional capacity to generate electricity was planned to be installed between 2012 and 2016 amounting to some 8,500MW. South Africa also has the ability to produce liquid fuels, however cannot provide in its overall demand. South Africa's wood-based biomass resources could be used to produce bioenergy via fast pyrolysis, either electricity or liquid fuels. Electricity is the more likely bioenergy product. The South African residual wood-based biomass resources are unlikely sufficient in quantity to cover beyond some 5MW electricity-equivalent of energy needs in specific locations (Chapter 9).

The assumption underlying the wood-based energy potential in Namibia and South Africa was based on even sized structure of bushes or trees. All projections take into consideration that only bush trunks (as measured in TE-units) would be used; not whole tree consideration. Projections were presented as a base case scenario under prevailing utilisation practices.

To translate the mass of wood residues to their energy content in Namibia, a wide range of data was compiled. The data is based on research carried out in order to estimate the energy content and possible commercial value of this biomass resource. Research was also carried out by Gore [308] in South Africa in the 1980 but did not include Namibian feedstock. Annual available wood-based biomass has been projected over a 20 year production cycle. A production cycle of 20 years was chosen to ease techno-economic modelling (Chapter 8). The principles of the harvesting and aftercare cycles were assumed to be alike in the Namibian and South African case (Table 5-4). The yield ratio (%) related to the total amount of biomass available per hectare; the wood yield level (%) related to the amount of wood available for bioenergy conversion per hectare.

6.3.1 Projections of wood based biomass available for bioenergy in Namibia

Under Namibian considerations, the farmland areas Okakarara and Otjiwarongo have been identified by this research as the wood-based biomass resource areas. The total amount of wood-based biomass that was available in Okakarara was 65.8Mt or expressed in bioenergy terms was some 1.12PJ in 2013; in Otjiwarongo was 192Mt or expressed in bioenergy terms was 3.28PJ in 2013. This total amount could be available to fast pyrolysis conversion for bioenergy production, as existing utilisation wood-based biomass was already catered for. Two models (Table 6-2) for annual extraction were investigated. Model 1 based extraction on a rate of 5% of total biomass available at any point in time; and for Model 2 the area from which biomass was proposed to be extracted is to remain constant for first time harvests, and also using the same harvesting schedules (Table 5-4). Utilising the harvesting schedules, and either extraction models, wood-based biomass from bush encroachment are projected to be available for more than 180 years.

Namibia currently offers only one biomass resource for potential conversion to energy, i.e. wood from bush encroachment. The main aim to harvest wood from bush encroachment is to improve livestock production systems, both in commercial and communal farmland areas. The harvest of wood from bush encroachment for bioenergy translates into various benefits: additional energy potential; and improved rangeland management to maximise livestock production. Actual conversion of the biomass was discussed in Chapter 7, 8 and 9 respectively.

6.3.2 Projections of available wood based biomass available for bioenergy in South Africa

South Africa offers a multitude of biomass resources which could be converted to bioenergy via fast pyrolysis. This research concentrated on wood-based biomass resources, and specifically on biomass obtained from woodlands production, bush encroachment and eradication of alien invasive wooded plant species. The current uses for these resources were discussed in sections 4.1.3.1, 4.1.3.2, 4.1.4 and 4.1.5 respectively. The energy requirements in rural areas of South Africa are vast, and are largely covered by harvesting of wood in natural or indigenous forests and woodlands. To cover commercial/industrial energy requirements through fast pyrolysis production systems, the residual wood-based biomass resources were assessed. Residues from invasive alien woody plants are declining over time. Wood-based biomass supply from bush encroachment in woodlands seems to remain stable over time.

The existing uses of the wood-based biomass were investigated and it was found that wood-based biomass potential for pyrolysis conversion was assessed to be in excess of 12Mt per annum over a 20-period. Although wood-based biomass resources from invasive alien plants (harvested by the WfW programme) are declining over time, this resource presents the largest potential for fast pyrolysis conversion. The resource is furthermore largely concentrated in two South African provinces, making the harvesting and conversion of it more economical than wood from bush encroachment or commercial forestry residues. The techno-economic assessment and viability of use of various wood-based resources follow in Chapters 7, 8 and 9 respectively. The amount of wood-based biomass available for bioenergy is based on discussions as presented in sections 4.1.3 and 6.2 respectively; a summary is provided in Table 6-6.

Table 6-6 Estimation of wood based biomass energy potential in South Africa, including consideration for current uses of biomass

Type	Average yield (Mt)	Annual average amount of residue already used (Mt)	Projected residues available for fast pyrolysis conversion (Mt)	Calorific value (MJ kg^{-1}) [308, 309, 310]	Projected annual energy potential	
					(PJ)	(Mtoe)
Woodlands/ Bush Encroachment	**~39.2**	**12** [154]	**27.2**	19.31 [159]	**0.53**	**0.01**
WfW alien species control programme	**5.42**	**1.52**	**3.90**		**73.06**	**1.75**
Western Cape	4.17	1.01	3.16	18.73	59.19	1.42
Eastern Cape	1.25	0.51	0.74	18.73	13.88	0.33

With regard to woodlands and bush encroachment species, as mentioned in Table 6-6, the species refer to indigenous *Acacia* species mainly, of which *Acacia mellifera*, is the main component. Within the group of alien species sought to be eradicated under the WfW programme in the Western and Eastern Cape, the most dominant species, are alien *Acacia* species and *Acacia mearnsii* is the focus, of which over 40 percent of invasion occurs in the area. Some *Eucalyptus* is also reported.

7 EXPERIMENTAL WORK

One of the objectives of this research was to evaluate and compare different feedstocks as available in Namibia and South Africa for fast pyrolysis. The feedstocks, i.e. wood based biomass, which have been tested, are described and characterised in this Chapter. The received condition of the feedstock and any preparation methods used prior to fast pyrolysis are also described.

The fast pyrolysis experiments used to evaluate the feedstocks were carried out in a 150g/h reactor system. The equipment was described and procedures for operating the pyrolysis system, analytical equipment and obtaining mass balance and analytical procedures were included. The results from experimental work on fast pyrolysis were used in modelling fast pyrolysis processes and describing the products from fast pyrolysis.

To the best knowledge, fast pyrolysis of Southern African feedstock were not carried out before. Experiments were considered necessary, else techno-economic modelling could not be carried out. Tests were carried out in a laboratory environment with no manual available; thus test and procedures were described in detail. The various types of analyses provide the information for respective components of the bioenergy model. Tests were performed on the feedstock, the solid products (char), liquid products (bio-oil) and gaseous products (condensable and non-condensable). The detailed analysis of bio-oil was essential to determine the viability of the bioenergy model.

The thrust of this overall research is at macro-level analysis to determine the suitability of a feedstock for energy production using bio-oil. Other valuable components found in the pyrolysis liquids need further examination. The quantity of organic materials found in the pyrolysis liquids does not influence the overall mass balance.

7.1 FEEDSTOCKS INVESTIGATED

The following section characterises the feedstocks used during the course of this work.

7.1.1 Namibian encroachment bush

The sample feedstock was obtained from the Bush Blok Project of the Cheetah Conservation Fund based at Otjiwarongo, Namibia [311]. The Bush Blok project leaders indicated that the majority of the feedstock (encroachment bush) is milled *Acacia* species, and that the feedstock contains large quantities of bark, branches, twigs and leaves and mainly consisting of *Acacia* *mellifera* spp. *detines*. The sample also contains some *Acacia reficiens, Colophospermum mopane* and *Dichrostachys cinerea.* The specific analysis of the relationship between bark, leaves and branch material vs. bark free stem material is unknown; a large amount of bark negatively impacts on the quality of the bio-oil. From the yield analysis of the bio-oil it is thus assumed that the bark content of the feedstock is high (Section 7.7).

In general, Namibian encroachment bush was received as freshly cut and hammer-milled chips in sizes above 100 mm. For fast pyrolysis processing feedstock preparation has to be carried out. To prepare the bush for the 150 g/hr reactor, further size reduction and screening was necessary.. To improve the yield of bio-oil the moisture content needed reduction to levels less than 10% on a dry weight basis (section 7.2).

7.1.2 South African wood-based feedstocks

The purpose was not to have tested all various species available for possible use for fast pyrolysis conversion in South Africa, but rather to exemplify that biomass resources available in South Africa could serve as source of energy (Chapters 2, section 2.3 and 4; section 4.1.3).

Three feedstocks have been used as a basis of analysis for experiments, two of which are commercially grown forest resources (*Eucalyptus* and *Acacia mearnsii* (Wattle)) but which are also declared as alien invader species in certain areas of South Africa; and one alien species (Bamboo) which grows wild in certain parts of South Africa. The properties of these species are described in the following sections.

7.1.2.1 Eucalyptus (mixture of E. grandis and E. saligna)

The sample of *Eucalyptus* used in the tests was obtained from commercial forest areas of Mpumulanga province in South Africa. The sample is *Eucalyptus grandis* (the majority of commercially grown *Eucalyptus* is of this sub-specie in South Africa [134, 138]) and was provided to the project in whole pieces of between 50 to 100 mm diameter and 300 mm length. The samples did not contain bark. The bark generally falls off naturally after trees are felled. The samples were collected at the time when study trips for this research were conducted to South Africa in 2006 and 2007.

7.1.2.2 Black Wattle (*Acacia mearnsii*)

The sample of Wattle (*Acacia mearnsii*) used in the tests was obtained from commercial forest areas of Mpumulanga province in South Africa. Material was provided to the research in pieces of between 50 to 100 mm diameter and 300 mm length. The samples contained bark which was only removed with difficulty even after prolonged, i.e. one week of air drying.

The samples were collected at the time when study trips for this research were conducted to South Africa in 2006 and 2007. Due to financial constraints, it was not possible to collect Wattle samples from the Eastern and Western Cape areas specifically. It is expected that there would be little variance in wood properties between Wattle growing in the Mpumulanga and Eastern / Western Cape respectively.

7.1.2.3 Giant Bamboo (*Thamnocalamus tessellatus*)

A sample of Giant Bamboo (*Thamnocalamus tessellatus*) used in the tests was obtained from the Western Cape province in South Africa.

Although the Conservation of Agricultural Resources Act was enacted in 1983, a private entrepreneur has proposed to authorities that Giant Bamboo could be planted in a limited space with the aim to provide a project run at the University of Stellenbosch [312] with a sustainable biomass resource to produce bioethanol, from the pilot until prototype phase. The Giant Bamboo obtained was harvested at 18 months old. Stems of 50 to 100 mm diameter were selected and pieces of 300 mm length were cut off and allowed to air dry in Namibia for 10 days before being taken to the UK for testing.

7.2 FEEDSTOCK PREPARATION

For the fast pyrolysis process particle size is of importance; of a suitable particle size, particle range and dry. It is acknowledged that other properties may have an influence on the results of pre-treatment or fast pyrolysis experiments (e.g. particle or feedstock shape, regularity, surface area and surface area/volume ratio). However, by using a small particle size for fast pyrolysis processes (less than 600μm) with a reasonably narrow range (355-500μm) it was hoped that these other factors were negligible. For all pre-treatment and fast pyrolysis experiments the feedstocks were prepared to the following conditions:

- Ground and screened to given particle size range – for fast pyrolysis typically 355-500µm; and
- Moisture content measured and where necessary reduced to the value less than 10% mf wt.%.

7.2.1 Size reduction for fast pyrolysis experimentation

It has been found that the feeder rate can be maintained at optimum levels of 100-150g/h by using particle sizes in the range 355-500µm. All feedstocks with which experiments were carried out needed size reduction. The first stage of size reduction was to reduce the size of the feedstock to less than 75mm to allow it to fit into the cutting mill.

A Fritsch cutting mill with an interchangeable screen was used to reduce the feedstocks' particle size. Screen sizes of 100, 250, 500µm and 1mm were available. In all cases a screen size of 500 µm was used. This was found to produce the majority of particles in the 355-500µm range. Some undersized particles were produced, but these were removed by screening.

7.2.2 Screening

After size reduction the feedstock was in a powder form with a particle size less than 500µm. It was desirable to have a particle size distribution as narrow as possible. Thus in order to maintain a narrow particle size distribution, but also to minimise the amount of feedstock wastage, i.e. undersized feedstock, a size distribution of 355-500µm was chosen. This was achieved by sieving the feedstock using standard test sieves of mesh size 500µm and 355µm. Oversized fractions were reground using the cutting mill and undersized fractions were saved in case further work required smaller particles – this was especially the case for South African bamboo.

Only South African bamboo as feedstock caused extensive blocking in the feed tube aperture (Section 7.3.1) and the feed tube in the reactor (Section 7.3.2). A whole day was spent to conduct experiments with this feedstock. It was found that this occurred due to the nature of the feedstock in combination with the nature of the size reduction and screening, which also allowed particles through which were bigger than the selected screen size. It was realised that South African bamboo typically tends to break into slender (undersized), but too long pieces rather than square sized pieces in the desirable size range. Thus a rectangular particle could pass through a screen in a particular orientation, but may not in another orientation. For the majority of feedstocks used, this problem was solved by double grinding of the feedstock. This removed long, thin rectangular or 'pin like' particles. For South African bamboo, double grounding did not solve feeding problems during fast pyrolysis experimentation. It is purely a matter of chance of which way a particle is oriented. By double grinding the feedstock the probability of pin-like particles remaining was reduced. Feedstock that had been ground once was found to occasionally block, whereas double-ground feedstock did not block the feeder aperture or reactor feed tube. However, finding reasons why double-grounding in the case of South African bamboo did not solve feeding problems was outside the scope of this work.

7.2.3 Moisture content

The method used for measuring moisture content was drying to ASTM standards [313, 314]. After the feedstock was prepared to the correct size distribution, approximately 1g was weighed (to 4 decimal places) and then placed in a pre-dried and weighed crucible, this was then placed in an oven at 105ºC for at least 24 hours. From previous experiments involving repeated weighing of drying wood samples this has been found to be an adequate time period to achieve constant weight. The crucible and sample were then re-weighed, and the moisture content of the sample was calculated on a dry feedstock basis. This technique was always carried out in triplicate and an average is taken.

7.2.4 Ash content

Ash content measurement was carried out in accordance with the ASTM method [313, 314]. Approximately 1g was weighed (to 4 decimal places) and then placed in a pre-dried and weighed crucible; this was then placed in an oven at 105ºC for at least 24 hours. The crucible and sample were then re-weighed and the moisture content of the sample was calculated on a dry feedstock basis (section 7.2.3). The crucible was then placed in a muffle furnace at 750ºC for a minimum of 6 hours before being removed and cooled in a desiccator for 1 hour before weighing (to 4 decimal places). The ash content was calculated on a dry feedstock basis. The ash content measurement of feedstock was usually carried out directly after the moisture content measurement, since the same crucible and pre-dried sample could be used. This technique was always carried out in triplicate and an average was taken.

7.2.5 Drying

Fast pyrolysis requires feedstocks in a relatively dry state, i.e. less than 10 wt.% moisture as measured by the method proposed in section 7.2.3. The quality of the bio-oil is negatively impacted if feedstock moisture content is above 10%. Feedstocks were dried where necessary by storing in a fan oven at a constant 105ºC for 24 hours.

7.3 FAST PYROLYSIS SYSTEM

The 150g/h fluidised system (Figure 7-1) consists of three sections: feeder, reactor and products collection. The approximate dimensions and operating methods are described in the following sections.

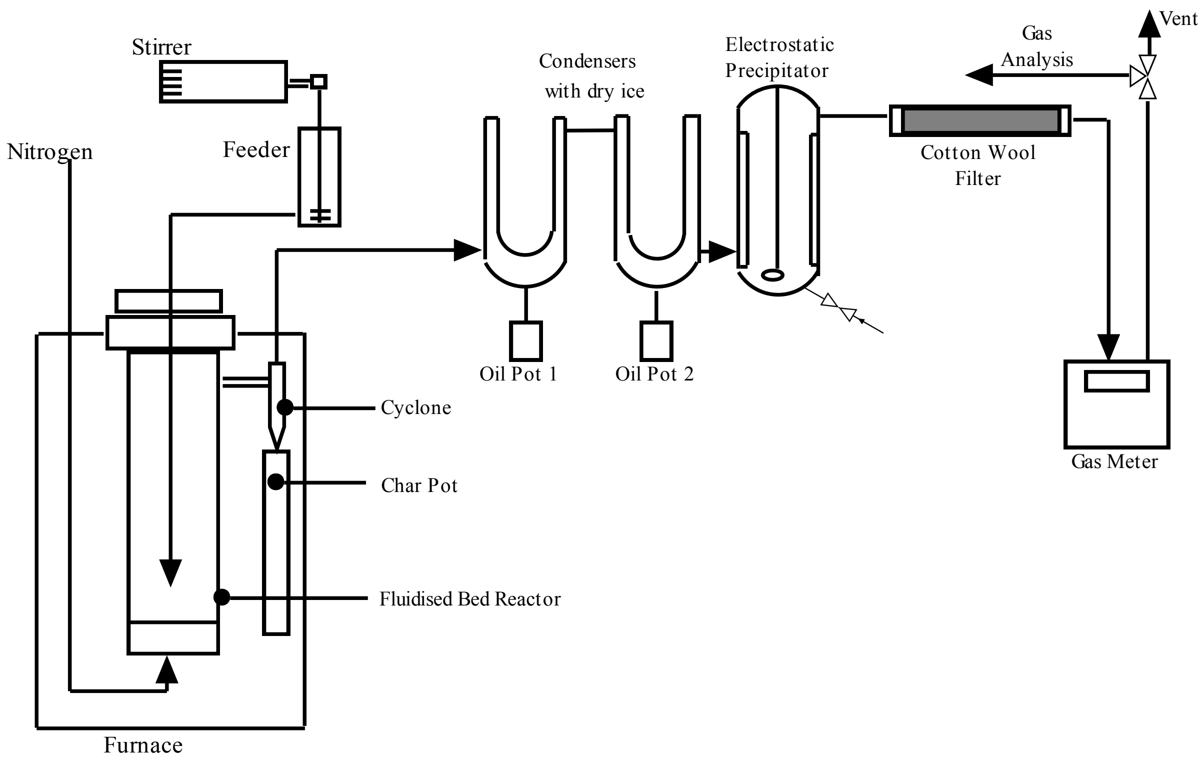

Figure 7-1 150g/h reactor and products collection system

7.3.1 Feeder

A diagram of the feeder is shown in Figure 7-2. The feeder consists of a cylindrical storage hopper, which is blanketed with nitrogen and slowly stirred by two paddles. Biomass is entrained through the feed aperture by a continuous flow of nitrogen into the biomass entrain tube, which crosses the hopper at the bottom. The biomass was entrained along the entrainment tube where it then passed into the flexible tube linking it to the feed tube in the reactor.

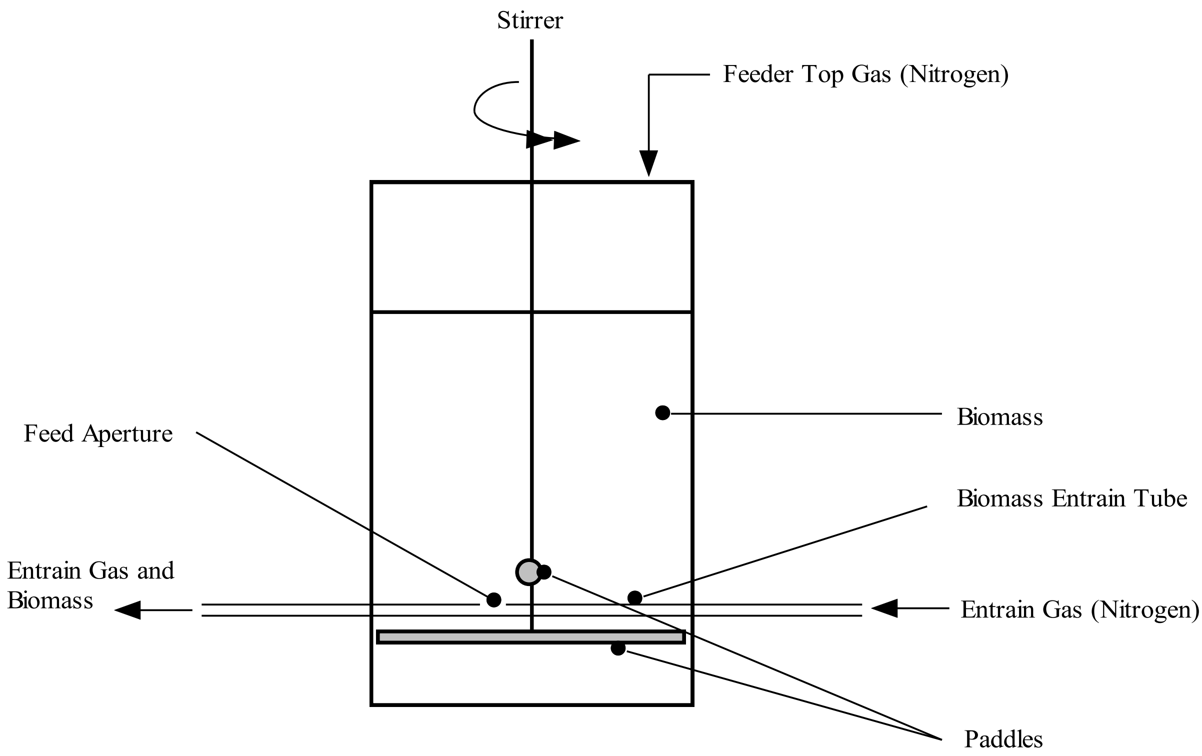

Figure 7-2 Schematic diagram of biomass feeder

The main body of the feeder is constructed from clear Perspex for a number of reasons. Firstly Perspex is a strong and robust material, which is easy to machine, thus allowing modifications or new designs to be quickly implemented. Secondly, since the Perspex is clear it was easy to observe the behaviour of the feedstock during a run, thus problems such as bridging or low feedstock levels could be observed and corrected. Further, Perspex is an easy material to clean and therefore it was easy to change feedstocks after a series of tests have been completed. Problems associated with using Perspex include electrostatic attraction of very dry material which sticks to the surfaces.

The factors which affected the biomass feed rate were the type of biomass used, its size, moisture content, shape, preparation method and the feeder variables, i.e. entrain tube aperture size, paddle speed, entrainment flow and feeder top pressure. For a given biomass prepared by the methods described in Section 7.2, the size, moisture content and shape were fixed. Therefore, the feed rate of the feedstock was controlled by the feeder variables, and strongly influenced by the type of biomass. For example, giant bamboo demonstrated extensive feeding problems making it difficult to complete test runs, especially when compared to eucalyptus.

Calibration

Every time a new feedstock was used, calibration of the feeder was carried out. A feed rate of 100-150g/h was desirable since this is the design rating of the equipment. It may be possible to run at higher or lower feed rates but this is not recommended. At feed rates higher than 150g/h the feed tube in the fluidised bed is prone to blocking and at very low feed rates, i.e. <50g/h, the dilution of the pyrolysis vapours by the nitrogen gas makes gas analysis difficult (Section 7.5.1).

The feed rate is a function of biomass type as feeder material. Thus it was necessary to calibrate the feeder each time a new biomass type was used. The entrain tube aperture has the most significant effect on feed rate for a given stirrer speed and nitrogen flow. For most feedstocks the 1.7mm aperture is suitable, but for some feedstocks, i.e. dry and powdery or more dense, a smaller aperture is required to reduce the feed rate to acceptable limits of less than 150g/h. Once a suitable aperture has been found (this is done by trial and error) the feed rate can be fine-tuned by altering the feeder top flow (changes pressure in feeder) or paddle speed (increases fluid behaviour around the entrainment aperture making it easier to entrain the biomass).

The feeder has mechanical paddles, which slowly rotate to prevent bridging of the feedstock and also to maintain accurate and continuous flow of the feedstock. The speed of feeder paddles can be adjusted, which allows the feed rate to be altered during a run.

The top feeder is pressurised with a small flow of nitrogen, which forces the feedstock through the feed aperture into the feed tube. This flow can be changed during a run to either increase or decrease the biomass feed rate. By increasing the flow rate the pressure in the feeder is increased, thus increasing the feed rate. It was found (by trial and error) that the feed rate is very sensitive to stirrer speed, and less sensitive to feeder top flow rate. The influence of paddle speed and feeder top flow rate are useful since they can be altered during a run to increase or decrease the flow rate. Alteration of entrainment gas flow can be done during a run but is not recommended since this makes up part of the fluidising gas and therefore should be kept constant.

7.3.2 150g/h Reactor

The reactor consisted of a 40 mm internal diameter 316 stainless steel tube with a length of 260 mm. The top of the tube is threaded allowing the top of the reactor to be removed for weighing, cleaning and to add/remove the heating/fluidising medium, sand. The top of the reactor has three apertures, one is for a thermocouple to measure the reactor internal bed temperature and the second and third are for the feed tube and air cooling line (Figure 7-3). The feed tube transports the feedstock into the centre of the fluidised bed. It can be air cooled by a pressurised flow of air, which prevents temperature sensitive feedstocks from being pyrolysed before they reach the fluidised bed.

The heating medium in the reactor was inert sand (also weighing approximately 150g) with a particle size of 355-500µm. This particle range is used so that the reactor operates on blow-through mode. This means that the fluidising flow rate (normally 7l/min) of the sand is enough to blow the pyrolysed biomass (char and vapours) completely out of the bed while the sand remains in the bed. The sand was fluidised using nitrogen, which was preheated by the furnace in-line prior to entering the base reactor. The nitrogen then passes into the base of the reactor and is distributed by a sintered inconel plate with a 100µm pore size.

The feedstock (wood-based biomass) was carried down the reactor feed tube in a stream of entrainment nitrogen into the centre of the fluidised bed. Once it left the tube it began to pyrolyse almost instantaneously, producing pyrolysis vapours and ultimately char. Once the biomass had reacted completely, it formed char particles with similar dimensions to the original biomass, but with between 10 and 25% of the original weight, depending on the feedstock used. This char is then carried out of the fluidised bed by the fluidising gas flow.

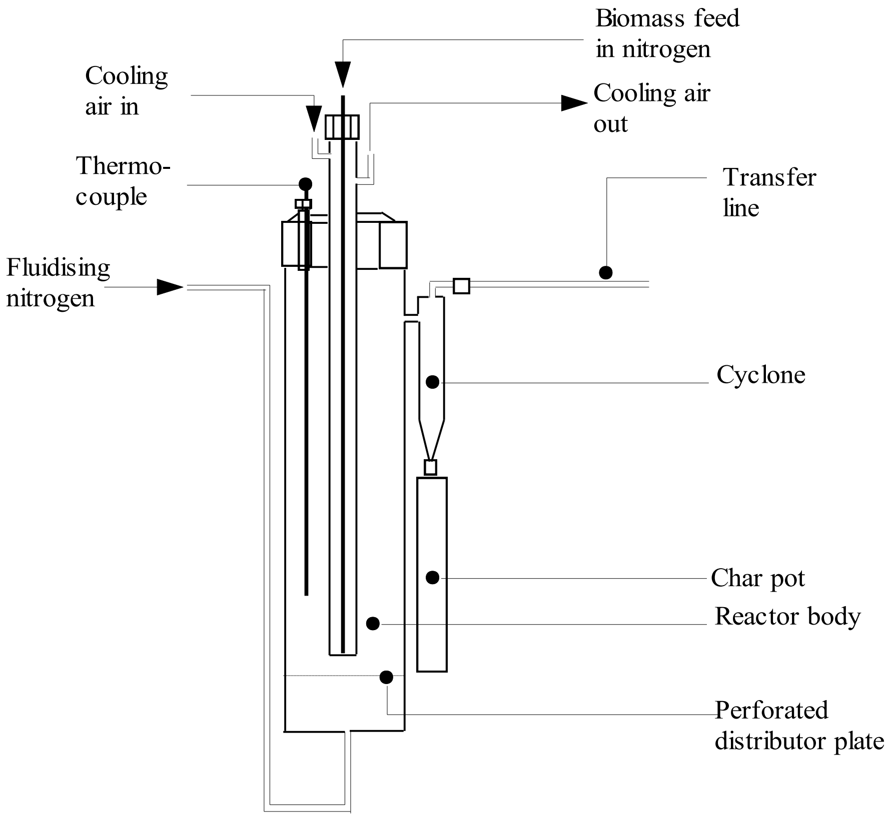

Figure 7-3 Schematic diagram of 150g/h fluidised bed reactor

The vapours and char then passed into the first stage of product collection, which is the cyclone. The cyclone was used to separate the char from the pyrolysis vapours. The pyrolysis vapours passed out of the cyclone via an outlet in the top and the char falls to the bottom of the cyclone where it passed into the char pot.

The reactor, cyclone and char pot sit in a vertical tube furnace, which maintains the temperature at a set-point. This can be controlled to a fixed point between 400 and 600ºC. The temperature of the reactor was measured by a K-type thermocouple placed directly into the fluidised bed. The furnace set-point was approximately 20ºC higher than the desired reactor temperature because energy was constantly required by the reactor to heat up the nitrogen and feedstock and perform the pyrolysis. To maintain a constant reactor temperature there must be enough excess heat available from the furnace to overcome nitrogen and feedstock specific heats and the pyrolysis heat of reaction. The furnace used a proportional controller linked to the thermocouple, which was independent from the reactor to maintain the set-point to within ±5ºC. The furnace thermocouple was mounted in the furnace wall at approximately 100 mm from the top.

The top of the furnace and hence the top of the reactor, cyclone and char pot was lagged to prevent heat loss. The outlet from the top of the cyclone to the second stage of the products collection system was also lagged to maintain pyrolysis vapour temperatures above 400ºC. This is very important, since below 400ºC the pyrolysis vapours start condensing. Vapour condensation can result in blockage of the transfer pipe between cyclone and second stage products collection, which would result in an early termination of the run.

7.3.3 Hot vapour residence time

Hot vapour residence time is the time that the pyrolysis vapours spend in the reactor system above 100ºC. There are two methods of hot vapour residence time measurement, reactor only residence time and total hot space residence time. The reactor, cyclone and char pot all sit in the furnace and are exposed to the temperature of the furnace. The vapours are kept at a constant temperature (around 200ºC) and could undergo secondary reactions. The reactor only residence time is not a realistic view of the time/temperature exposure of the vapours, since once the vapours leave the reactor they are still exposed to the furnace temperature. In all cases the residence time reported will be the total hot space residence time since this represents a more realistic view of the time/temperature of which the vapours are exposed to.

The volumetric throughput of the reactor is the volume of gas at the average reactor temperature passing through the reactor system in a given time. The total hot space of the reactor system is the volume of the reactor (above the distributor), cyclone and transfer line, discounting the volume taken up by the sand. The total hot space residence time is calculated from the volumetric throughput of the reactor system divided by the total hot space of the reactor. Once the pyrolysis vapours leave the hot space and enter the liquids collection system, condensation starts and the liquid products will start to collect.

7.3.4 Liquids Collection System

The liquid products collection consists of a water cooled condenser, an electrostatic precipitator, dry ice acetone condenser and cotton wool filter (Figure 7-1). All of the liquids collection system was constructed from glass for easy cleaning and also for the behaviour of the condensing pyrolysis vapours to be observed. The first cooled condenser had a cold finger filled with ice (0ºC). This cooled the pyrolysis vapours from around 400ºC to 50ºC and started the condensation process. The heavy ends were condensed by the first condenser, collected on the inner wall and dripped down to collect into oil pot 1 (OP1). The second condenser had a cold finger filled with dry ice and acetone (approximately -80ºC). This further cooled the pyrolysis vapours from around 50ºC to 5ºC. The light ends and water were condensed by the second condenser, collected on the inner wall and dripped down into oil pot 2 (OP2).

The electrostatic precipitator (EP) was located between the second condenser and the cotton wool filter. The EP was very effective at removing the remaining aerosols which were present in the gas after the second condenser. It used a 15,000V negative charge on a thin stainless steel wire suspended in the centre. This charged the aerosols, which were then attracted to the positively charged plate on the walls of the EP. The pyrolysis liquid ran down the walls of the EP and collected in the flask at the bottom where they were drained off during or after the run. It is not of absolute necessity to include an EP, however having the EP in the products collection system meant that the cotton wool filter (described hereafter) collected only a small fraction of the total pyrolysis liquids (less than 2% liquid base) and was used as a fail-safe to protect downstream equipment, i.e. gas meter and gas analysis equipment. Also, much less cotton wool was required and the pressure drop over the cotton wool filter was lower at the start of and during a run. It further ensured that only clean, non-condensable gases entered the gas meter and gas sampling/analysis system.

The cotton wool filter was a glass column, which was densely packed with around 40g of dry cotton wool. This formed a dense filter, which acted as a guard that no vapours exited and then entered the gas metre. However, during a run, as the vapours condense on the cotton wool the pressure drop over the cotton wool increased (starting off at approximately 50 inches H_2O and often rising as high as 150 inches H_2O). As the pressure increased there was a danger that the oil pots could be blown off; the run would be stopped if the pressure reached 150 inches of H_2O. Although the cotton wool was efficient at collecting vapours it was difficult to remove the pyrolysis liquid from the cotton wool after the run. Only by using solvent (ethanol) could the pyrolysis liquids be completely removed. In order to analyse the chemicals in the pyrolysis liquids, the solvent had to be removed. However, even low pressure distillation of the pyrolysis liquid and solvent mixture lead to losses of volatile components from the pyrolysis liquid (bio-oil), therefore it was better to use a bio-oil collection method that does not require solvent washing.

After the cotton wool filter was a gas meter. The gas meter measured the total volumetric throughput of gas through the system and was required to allow the gas to be analysed volumetrically for mass balance purposes and gas analysis (Section 7.4).

7.4 MASS BALANCE

The products of fast pyrolysis were separated and collected into three distinct categories, i.e. char, pyrolysis liquid (bio-oil) and gas. These three categories have been defined, also for mass balance purposes in Chapter 2.

7.4.1 Mass Balance Reporting

Table 7-1 shows a typical table, which is used for mass balance reporting. The experiment number has the prefix SFB (small fluidised bed) followed by the number. The temperature is that of the reactor and is the average recorded temperature from the bed thermocouple. The temperature is taken manually at 1 minute intervals throughout the course of the run, the temperature reported is the average reactor temperature for a particular run. The total hot space residence time is shown next, this is calculated by the method described in Section 7.3.3.

Table 7-1 Example of mass balance reporting

Run No.	SFB
Temp. (ºC)	Fluid bed in-bed average temperature
Res. Time (s)	Average total hot space residence time
Feed rate (g/h)	Average rate at which feedstock is fed into the reactor
Moisture (mf wt.%)	Moisture content of feedstock
Ash (mf wt.%)	Ash content of feedstock
Yields (mf wt.%)	Major product yields on a dry feedstock basis
Char	Analysis method Section 7.4.2
Organics	Analysis method Section 7.4.3
Gas	Analysis method Section 7.4.4
Water	Analysis method Section 7.5.2.1
Total liquids	Sum of organics and water
Closure	Percentage of feed/input recovered as products
Gas (mf wt.%)	Gas yields on a dry feedstock basis
Carbon Monoxide	Yield of carbon monoxide
Carbon Dioxide	Yield of carbon dioxide
Methane	Yield of methane
C_2s	Yield of ethane and ethylene
C_3s	Yield of propane and propylene
Gas (nitrogen free, vol.%)	Gas yields on a volume basis not including nitrogen
Carbon Monoxide	Volume of carbon monoxide
Carbon Dioxide	Volume of carbon dioxide
Methane	Volume of methane
C_2s	Volume of ethane and ethylene
C_3s	Volume of propane and propylene

The rate at which the feedstock is fed into the reactor is shown in grams per hour (g/h). The feed rate should be kept between 50 and 150 g/h to maintain consistency and accuracy during a run (section 7.3.1). Low feed rates can result in poor gas analysis and high feed rates can result in overloading the reactor and collection system leading to blockages. The feed rate was calculated by weighing the feeder (±0.01%) before and after the run. The feedstock was not weighed alone since the small particle size meant it was difficult to handle, which could have introduced inaccuracies. The average feed rate is the difference in feeder weights (before and after) divided by the total run time in hours. The moisture and ash content of the feedstock was calculated by the methods described in Section 7.2.3 and Section 7.2.4 respectively.

The yields of fast pyrolysis products were reported on a moisture free feedstock basis. The char was calculated as per Section 7.4.2; the organics were calculated as described in Section 7.4.3; the gas yield was calculated by the method described in Section 7.4.4; and the water of pyrolysis was calculated by analysis of the organics as per Section 7.5.2.1. The total liquids were measured by weighing (Section 7.4.3) and this contains both organics and water of pyrolysis. The closure is the percentage of the original feedstock which has been recovered. It gave a measure to assess the quality of the experiment, since a poor closure (i.e. less than 90wt% or in excess of 100%) indicated that something has not been measured or accounted for correctly. In most cases the closure is in the region of 95-100wt%. Reasons for incomplete closure are discussed in Section 7.6.

The gas yields were further sub-divided into the incondensable gases carbon dioxide, carbon monoxide, methane, C2s (e.g. ethane, ethylene) and C3s (e.g. propane, propylene). Other gases (e.g. hydrogen, n-butane, and n-butylene) were analysed for but are rarely detected so were not included in the mass balance reporting. All gas yields were given on a weight percentage dry feedstock basis and also on a nitrogen free volume basis.

7.4.2 Char

Char is a black, solid substance that is collected in the char pot as a residual coating on the sand, reactor, char pot and cyclone, and as some of very small particle sizes blow through into the liquids collection system. The reactor, cyclone and sand are assumed to remain at a constant weight, so any increase in weight was due to char. It is feasible that the sand will be worn away by attrition, but this effect has been assumed to be minimal.

The reactor and cyclone were weighed before and after a run (±0.01%) and the difference is assumed to be char. The coating on the sand was quantified by weighing the sand before and after a run, the difference again being char. The contents of the char pot was also classed as char and again are weighed. In both cases the weighing was to 2 decimal places and was accurate to ±0.01g. It is possible that some of the sand was blown into the cyclone and therefore the char pot, but since sand was weighed before and after it would be accounted for through establishing the differences in weight.

The char which was blown through the cyclone and into the liquids collection system tended to stick to the glass walls and can be filtered from the pyrolysis liquid washings (section 7.4.3). However, any char which could get into the liquids is very difficult to remove, since the pyrolysis liquids must be diluted with a suitable solvent (ethanol, methanol or acetone) before they will pass through a filter. Dilution of the pyrolysis liquids by solvents will result in loss of volatile components when the solvents are removed. It should be noted that the pyrolysis liquids contain a small amount of microfine char (less than 20μm), this was too fine to remove by filtration and therefore had to remain in the liquid (section 7.3.3)

7.4.3 Liquids

The collection of the liquid products begans in the first (ice) condenser. They were collected on the walls of the first and second condensers, where they run down the walls into oil pots I and II which are located at the bottom of the condensers respectively. They were also collected in the EP, where again they ran down the walls to be collected in the flask at the bottom of the EP. The oil pots were weighed (to the accuracy of ±0.01g) before and after the run and the difference was pyrolysis liquid. The condensers and the EP were weighed before and after the run (to the accuracy of ±0.01g). The liquids from the oil pots I, II and EP were placed into separate storage containers for subsequent water and chemicals analysis. Any liquids remaining on the glassware were washed off using ethanol, this was then filtered to remove char using pre-dried and weighed Whatman No. 1 qualitative filter paper. The filtered liquids had their water content analysed using Karl Fischer coulometry (Section 7.5.2.1) and were then stored as washings.

The pyrolysis liquids are further sub-categorised into organics and water. The organics are classified as the total liquids (difference in weight of the glassware and cotton wool) less the weight of char and water. The water comes from the feedstock's original moisture content and also from water of pyrolysis (formed as a product of the pyrolysis reaction). The total water content of each of the pyrolysis liquid samples (OPI, OPII, EP and wash) was measured by Karl Fischer coulometry. The total water from the pyrolysis liquids (i.e. the sum of water from the four samples) had the original feedstock water content subtracted from it, thus the water product quoted in the mass balance is the water of pyrolysis.

7.4.4 Gas

The volumetric throughput of the fluidised bed reactor system is measured using a Schlumberger Remus 3G1.6 total gas meter (Figure 7-1). This measures the total gas throughput in cubic metres to three decimal places and is accurate to ±2.0% of the total hourly flow rate. After the gas meter a gas pump was used to take representative samples throughout the course of the run, usually three or more samples are taken for subsequent gas chromatographic analysis (section 7.5.2.2). The samples were analysed for their volumetric content of the major pyrolysis gases, which are carbon monoxide, carbon dioxide, hydrogen, methane, ethane, propane, propylene, n-butane and n-butylene. It was assumed that the remainder of the pyrolysis gas is made up of nitrogen. From this analysis the volumetric constituents of the pyrolysis gas could be calculated and hence the weight of gas produced.

7.5 PRODUCT ANALYSIS

Accurate measurements and analysis are essential to any experimental-based project. The following section describes analytical techniques used to quantify the major pyrolysis products and produce good quality reproducible mass balances by accounting for material entering (the feedstock) and leaving (fast pyrolysis products) the system.

7.5.1 Gas Analysis

Gas samples were taken periodically during the course of the run. These samples were analysed for pyrolysis gases using gas chromatography. Three separate systems were used to detect the full range of gases. Hydrogen, oxygen, nitrogen and carbon monoxide were detected using a molecular sieve column, carbon dioxide was detected using a Poropak Q column and C1 – C4 gases were detected using a picric acid column.

Gas chromatography (GC) is an analytical technique which relies on the comparison of gas concentrations. For every gas analysed, a standard gas, with a known concentration and of similar concentration to that expected in the pyrolysis system exit gas, has to be injected into the column and the peak residence time and area noted. This residence time will then correspond to that particular gas as under the specific conditions for that GC system and column. Thus, when a gas sample is injected, only the gases, which have been previously analysed and calibrated, can be identified and quantified. By using several standard gases, the concentrations of all the major pyrolysis gases can be identified and quantified. From the total volume measured by the gas meter the mass pyrolysis vapours produced can then be calculated.

The pyrolysis vapours are dilute because the fluidised bed reactor requires a high throughput of gas (6-18 l/min, nitrogen was typically used) to keep the sand fluidised. Extra gas is also required to entrain the biomass from the feed and into the reactor (2-5 l/min). The extra gas means that the pyrolysis vapours only make up approximately 2% (volume basis) of the total volume output of the reactor system, as measured by the gas meter.

The main problem with the GC systems described above is that the sensitivity has to be turned up to detect the low concentrations of gas. The concentrations of gas, which the GCs detect is usually in the range of 1.00% (total gas volume basis), for abundant gases such as carbon monoxide and dioxide, down to concentrations as low as 0.02% (total gas volume basis) for minor gases such as butane and n-butylene.

Other problems are specified to particular detection systems, thus the molecular sieve column uses helium as a carrier gas, unfortunately this tends to mask most of the hydrogen it is detecting so only concentrations greater than 1.0% can be detected. As mentioned above, it is unlikely that any minor product gas would be found in such high concentrations, thus the small volume of hydrogen, which is produced in every run is an unquantifiable loss. This loss could be estimated, however this was not done since all mass balances are reported in a format where everything had been measured directly.

7.5.2 Pyrolysis Liquid Analysis

The main product of biomass fast pyrolysis is pyrolysis liquid called bio-oil. It contains water, char fines and organic compounds derived from fragmentation and depolymerisation of cellulose, hemicelluloses and lignin polymers. The pyrolysis liquids were collected as 4 discreet samples from the pyrolysis system, oil pots I and II, EP and washings. All 4 of these samples had to be analysed for water content (using Karl Fischer coulometry/titration,), chemicals and elemental content (using HPLC, and using CE-440 and Carlo Erba elemental analysers,) and molecular weight (using PL-GPC50 system).

7.5.2.1 Water Content Measurement by Karl Fischer (KF) Titration

A Mitsubishi, model CA-20, KF coulometer was used for quantitative determination of water in pyrolysis liquids. Due to the relatively high water content and sometimes high viscosity of the pyrolysis liquids and the sensitivity of the coulometer, the pyrolysis liquids were diluted using methanol before being analysed. If the liquids were not diluted they would require much more reagent (hence increased cost), would take more time or may not dissolve in the coulometer properly and give low (false) readings.

To find the water content of the pyrolysis liquid, a small amount is first weighed into a vial. This is then diluted (by at least 1:10) with a known weight of methanol with a known moisture content. A known weight (±0.02%) of combined liquid is injected through a septum directly into the meter. The meter then determined the amount of water contained in the injected sample and, since the weight of the combined liquid was known, the percentage water was calculated. The coulometer gives a moisture content, which is reproducible and accurate to ±0.01wt.%.

7.5.2.2 Chemical (HPLC) Analysis

HPLC (High Performance Liquid Chromatography) was used to determine the concentration of some chemicals contained in the pyrolysis liquids. HPLC is a similar technique to GC, in that the analysis is achieved by comparison to previously identified chemicals with known concentrations. Thus, as for GC analysis, a standard is required which contains the chemicals and which are expected to be in the pyrolysis liquid in similar concentrations. The standard contains the following chemicals in specified concentrations (typically 0.1-2 wt.%) glyoxal, xylitol, levoglucosan, hydroxyacetaldehyde, formic acid/formaldehyde, acetic acid, acetol, methanol, 2-furoic acid, cyclotene, cellobiosan, glyceraldehydes, ethanol, fructose and glucose.

HPLC uses a 0.05wt% sulphuric acid solution as mobile phase. The mobile phase is constantly pumped through the column and carries the sample to be analysed. Hence only water-soluble compounds in the pyrolysis liquids can be analysed. The samples were prepared by weighing out an amount of pyrolysis liquid into a pre-weighed plastic vial. A known weight of mobile phase was then added to the vial to dilute the pyrolysis liquids (about 4 part mobile phase to 1 pyrolysis liquid). The sample was shaken and the water insoluble fraction formed a precipitate known as pyrolytic lignin. The plastic vial was centrifuged for 5 minutes at

4,000rpm to remove the precipitate. The water soluble pyrolysis liquid fraction was poured out of the vial and filtered using a Gelman Acrodisc PTFE filter (0.2μm pore size) to remove any remaining liquid. The filter was used as a precautionary measure to prevent lignin entering the HPLC system and damaging the analytical columns. The precipitate remained in the sample vial and after several hours of drying the remaining fraction was weighed and was classified as pyrolytic lignin. The HPLC system uses a Bio-rad column which is linked to a refractive index detector. The filtered water soluble sample is injected into the column and after approximately 30 minutes a trace showing the chemicals detected and their areas was produced. The software package then integrated these areas and compared them with the standard, thus the chemical concentrations could be found.

7.5.2.3 Elemental Analysis

The liquid fraction from oil pot 1 was taken and subjected to CHN analysis using CE-440 and Carlo Erba elemental analysers with ±0.3% absolute accuracy. The analysis was undertaken by MEDAC Ltd., Surrey, UK. After obtaining the carbon, hydrogen and nitrogen (CHN) contents of the liquid samples, the oxygen content of the pyrolysis liquids was derived by difference.

The elemental analysis does not have direct relevance to the fast pyrolysis process, but was important for the determination of the higher heating value (HHV) of the pyrolysis liquid, based on a correlation developed by Parikh, Channiwala and Ghosal [315] shown by Equation 7-1.

Equation 7-1 Higher Heating Value for Liquid Fuels

$$HHV_{dry}(MJ/kg) = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.015N - 0.0211A$$

Where C, H, O, N and A represents mass percentages on dry basis of carbon, hydrogen, oxygen, nitrogen and ash contents of feedstock respectively. The C, H, N and O contents of feedstock were obtained by the elemental analysis as mentioned above. The sulphur content is not taken into account because it is lower than the detection limits of the instrument (<0.1wt.%). The ash content of the pyrolysis liquids were estimated by assuming that the solids present in the pyrolysis liquids contained 5wt.% of ash as determined by the ASTM method (section 7.2.4) for solids.

The heating values were calculated on a dry basis. To calculate the values on as-produced or wet basis, Equation 7-2 was applied taking into account the water content of the pyrolysis liquid (H_2O, wt%). The lower heating values were calculated from HHV and the hydrogen content by Equation 7-2

Equation 7-2 Lower Heating Value for Liquid Fuels

$$LHV_{wet} = LHV_{dry}(1 - H_2O/100) - 2.442 \times H_2O/100$$

7.5.2.4 Molecular weight distribution

Molecular weight distribution of pyrolysis liquids was determined using the gel permeation chromatography (GPC) technique. An integrated GPC system, PL-GPC50 from Polymer Laboratories, UK, equipped with a PLgel 3µm MIXED-E column, 300x7.5 mm, and a refractive index (RI) detector. The detector temperature is set at 40ºC. Liquid samples were dissolved in HPLC-grade THF (Tetrahydrofuran) solvent at a concentration of 0.01 g/ml and were filtered through a 0.2 µm Millipore Millex-GN nylon filter to avoid column plugging by solids or insoluble impurities. Approximately 100 µm of the prepared samples was injected using a PL-AS RT GPC autosampler. HPLC-grade THF was used as an effluent with a flow rate of 1 ml/min. Prior to the measurement, GPC calibration was made with a series of polystyrene calibration standards with molecular weight range of 162-19880 g/mol. Calculation of molecular weight averages was done by Cirrus 3.0 software. The software offered two methods of data calculation, namely height based and area based. Height based calculation is analogous to the integrator packages of the late seventies and uses a simplified method of calculation, whereas area-based calculation is the rigorous treatment of data and the method of choice for accuracy work [316]. This was used for this research. The number average molecular weight (Mn), weight average molecular weight (Mw), molecular weight at highest peak (Mp) and polydisperity (PD = Mw/Mn) were calculated by the software based on the refractive index (RI) signal and the calibration curve obtained.

7.5.3 Elemental Analysis of feedstock char

A sample of both the biomass and char was subjected to CHN analysis using CE-440 and Carlo Erba elemental analysers with ±0.3% absolute accuracy. The analysis was done by MEDAC Ltd., Surrey, UK. After obtaining the carbon, hydrogen and nitrogen (CHN) contents of the liquid samples, the oxygen content of the pyrolysis liquids was derived by difference.

The elemental analysis does not have direct relevance to the fast pyrolysis process, but was important for the determination of the higher heating value (HHV) of the feedstock and solids derived from the pyrolysis process, based on a correlation developed by Parikh, Channiwala and Ghosal [317] as shown by Equation 7-3. The lower heating values were calculated from HHV and the hydrogen content by Equation 7-2.

Equation 7-3 Higher Heating Value for Solid Fuels

$$HHV_{dry}(MJ/kg) = 0.3536FC + 0.1559VM - 0.0078A$$

Where FC, VM and A represent mass percentages on dry basis of fixed carbon, volatile matter and ash contents of feedstock, respectively. The elemental contents of feedstock were obtained by the elemental analysis as mentioned above as well as through the gas analysis during a specific pyrolysis run. The ash content was taken as determined by the ASTM method explained in Section 7.2.4. All heating values were calculated on a dry feedstock basis.

There should also be consideration of slow and fast pyrolysis methods for the determination of the HHV of a solid fuel. The Equation 7-3 presentation of the HHV has more relevance to slow pyrolysis processes where the FC and VM were determined by chemical analysis of the char product. The FC and VM are technology dependent variables and thus are likely to produce different values depending on the process conditions and the fast pyrolysis technologies used.

Equation 7-2 can also be used to determine LHV for the solid fuels. However, in many instances when the LHV for solid fuels is required, published data can also be accessed for a variety of wood-based feedstocks and their solid products [310].

This research concentrated on conducting as many as possible varying fast pyrolysis test runs with the four wood-based biomass types. Compositional analyses of the biomass and fast pyrolysis were conducted by MEDAC Ltd. The data on composites required for computing lower and higher heating value of the biomass (4 types of wood), char and pyrolysis liquid (bio-oil) was available. This saved time and costs to also measure energy content of the various feedstock and products. The accuracy using indirect calorimetry was acceptable for this research.

7.6 EXPERIMENTAL ACCURACY

The experimental results presented are believed to be the best achievable from the equipment available at Aston University. However, this does not necessarily mean that they are 100% accurate. In all stages there is an element of error, inaccuracy or non-quantification of a product or products resulting in incomplete closure. The point of this is to highlight the areas of the mass balance that are believed to be incomplete or less accurate, suggest possible reasons and predict the effect on the mass balance.

Table 7-1 detailed all areas of mass balance reporting, however, this can be summarised into four categories:

- Feedstock parameters;
- Process conditions;
- Mass balance yields;
- Product analysis.

7.6.1 Feedstock parameters

The major feedstock parameters were moisture content and ash content. The moisture content was measured (section 7.2.3), with a reliable method accurate to ±0.1wt% (dry feedstock basis). However, due the hygroscopic nature of biomass, it will naturally absorb moisture from the air. The likelihood of this is increased if the moisture content is reduced (i.e. by drying in an oven). Thus, although moisture content of a feedstock may be correct at the time of measurement, if left open to atmosphere, improperly stored or stored for a long period of time, the moisture may change, typically increase to the equilibrium moisture level. The moisture content was measured at the time of performing the experiment.

The moisture content of the feedstock played an important role in the mass balance since the original moisture is discounted from the water in the pyrolysis liquids (to leave water of pyrolysis).

The ash content was measured after the moisture content and was calculated on a dry basis, thus inaccuracies in the moisture content could have a compound effect on the ash content. Unlike the moisture content, the ash content does not have such a significant effect on the mass balance. However, ash does have a significant effect on the pyrolysis reaction. Ash may accumulate in the reactor resulting in lower than expected bio-oil yield. Ash may form when the reaction temperature is not well controlled or oxygen leaks into the reactor. Controlling the process by closely monitoring of set temperatures is key. Additionally, before starting the fast pyrolysis process, it was cross checked that all apertures were correctly fitted.

The feed rate was measured as the difference in the feeder weight (before and after a run), divided by the total run time, hence an average. It may seem less accurate to weigh the total feeder rather than the feedstock. However, due to the nature of the fine biomass particles (i.e. sawdust), it was difficult to pour and tended to become charged with static from the stirrer, thus was very difficult to weigh separately. So, although the feeder was weighed to ±0.01% this is more accurate that trying to pour the biomass into and out of the feeder to weigh to ±0.001%.

The elemental analysis (CHN) of the biomass or feedstock was measured with a 0.3% absolute accuracy and subsequently the higher and lower heating values of the feedstock are influenced accordingly.

7.6.2 Process conditions

The key process conditions are the temperature (i.e. average fluid bed, reactor freeboard) and residence time. The reactor temperature was measured directly from a K-type thermocouple located in the fluidised sand. The temperature was maintained by a furnace which surrounds the reactor, cyclone and char pot. The reactor temperature was measured manually at set time intervals throughout a run and noted. At the end of a run the average reactor temperature was calculated. The average reactor temperature may not adequately describe the temperature of the reactor, since the run could have consisted of 30 minutes at 450ºC, followed by 30 minutes at 550ºC, which is an average of 500ºC. This could have been tested more rigorously if the average was taken based on more frequent readings with standard error. However, the average reactor temperature provided a fair indication of the temperature the reactor was maintained at during a run.

It was important to know the total hot space residence time as this measures the amount of time the pyrolysis vapours were exposed to the reactor temperature. This gives an indication of the amount of secondary reactions which may have occurred. The total hot space residence time (Equation 7-4) is a function of the volume of the total hot space, weight of sand in the reactor, density of the sand, total volumetric measurement, total run time and average reactor temperature. Thus any error in the measurement of these variables will result in an error in the residence time.

Equation 7-4 **Total hot space residence time**

$$Residence\ Time_{total\ hot\ space\ units} = \frac{\left(Volume_{TotalHotSpace} - \frac{W_{sand}}{\rho_{sand}}\right) \times 60 \times T_{thermocouple} \times Time}{1000 \times T_{reactor} \times Volume_{total\ throughput}}$$

The total volume was measured at the temperature of the system which is usually the reactor temperature. The volume of the total hot space and the density of the sand are constants. The weight of sand is accurate to ±0.01g and therefore is unlikely to introduce errors into the residence time calculation. The reactor temperature is an average, so could be a potential source of error. However, in this calculation it was used to calculate the total volume of gas at the reactor temperature and since an average volumetric throughput of gas was calculated, it was best to use the average reactor temperature. The total run time was measured ±1s and since a run usually lasts at least 30 minutes, there is virtually no error from this variable.

Table 7-2 **Residence time error analysis**

Variable	Typical	Minimise	Maximise	Deviation
Sand (g)	150.00	150.01	149.99	±0.01
$T_{measurement}$ (°C)	0	-5	5	±5
Time (s)	1800	1799	1801	±1
T reactor (°C)	500	505	495	±5
$Volume_{total\ throughput}$ (dm^3)	400	408	392	±2%
$Residence\ Time_{total\ hot\ space}$ (s)	0.51	0.49	0.53	
Percentage Error		4.43	4.65	

7.6.3 Mass Balance Yields

Mass balance yields were categorised into char, liquids (including organics and water) and gas. The closure was the difference between input as biomass (dry) and the total outputs usually expressed as a %. The way in which each input and output was calculated was discussed in section 7.4.2 (Char), 7.4.3 (Liquids) and 7.4.4 (Gas).

Char is collected in the char pot, as a coating on the sand and inside the reactor, and could therefore be weighed directly, making it simple to quantify. However, the small microfine char tended to be blown through the cyclone and into the liquid collection system where it collected in the pyrolysis liquids. It was very difficult to remove this char from the liquids, (section 7.3.4), this was not practical. The level of char in the liquid is generally very low (typically less than 0.05 wt%). Since the char in the liquids was classed as liquids, it did not lead to reduced closure, only to incorrect classification.

The liquids were collected in the oil pots (OPI and OPII which are located at the bottom of the condensers) and the EP (section 7.4.3). Similar to the char, the liquids were weighed directly (either to 1 or 2 decimal places), thus it was unlikely that any error was introduced here. As mentioned above, some char may have been blown into the liquids, thus giving a slightly inflated liquids yield. However, this was minimal. Water content measurement of the liquids was accurate to ±0.01 wt%, so it seemed unlikely that this could introduce errors into the organic/water categories.

The most likely source of error in pyrolysis liquids yield estimation was the hold up in equipment and possible loss of water and/or volatile organics from the liquids collection system. Since large volumes of fluidising and entrainment gas (nitrogen) are used, this will act as a carrier gas and could carry a small percentage of the more volatile components out of the collection system and into downstream equipment. It was difficult to quantify on a general basis, since each feedstock and reactor temperature resulted in the production of a certain yield of volatile components. For any run it was uncertain how much volatile organics was produced and hence lost. If it were possible to analyse the gas more accurately, then perhaps these losses could be quantified. Until more sensitive gas analysis is possible then the loss of water and/or volatile organics must remain an unquantified loss.

Unlike the char and liquids, which were measured after the fast pyrolysis run, the gas was measured directly during a fast pyrolysis experiment. Although the total volumetric throughput was known, the amount of fluidising and entrainment nitrogen was not measured. This could be estimated from the rotameters, which were used to measure the nitrogen flows. However, sometimes these flows were altered during a run. In the future, a gas meter could be placed on the nitrogen inlet to give an indication of the nitrogen consumption. Even if both the nitrogen input and total gas outputs were known this would only give an indication of total gas volume, the gas composition and therefore, weight would still have to be determined.

Determination of the gas composition is carried out by chromatography (section 7.5.1). Possible inaccuracies were discussed in section 7.6.4.

7.6.4 Product Analysis

The product analysis were split into three categories: solids, gas and liquids analyses. The liquids analysis can be sub-divided into water (Karl Fischer Coulometry), chemicals (HPLC) and molecular weight analysis.

The gas analysis is probably the weakest part of the mass balance. When closure is low it is usually due to poor detection of the non-condensable gases due to the high dilution. Also, it is possible that some water and/or volatile organics escape undetected as vapour, which could also lead to poor closure in the mass balance. The closure was not low for every run, thus it would be incorrect practice to estimate vapour losses for runs with low closures and not for runs with good closure (95-100%). The loss of vapour can be estimated from the total volumetric throughput and partial pressures of components which were believed to be lost (i.e. water and volatile organics).

Although the gas analysis was the weakest part of the analysis, it was not due to poor equipment. The problem was that the equipment had to be turned up to its limits of detectability and hence was performing at its most upper range. However, in the absence of any other method of gas analysis this method must remain.

The Karl Fischer system and method was described section 7.5.2.1, and was accurate to 0.01wt%, thus not believed to have been a source of inaccuracy or poor closure.

. The accuracy of HPLC analysis (section 7.5.2.2) was of less importance to this work as the major objective of having analysed the liquids lied with identification of possible organic components in the liquids and not with the accuracy of the identified quantities. The number of test runs on component analysis in liquids were also too few to warrant accurate measurement.

Establishing the molecular weight is independent of water content and chemical content analysis and does not influence the result of the latter measurements. Molecular weight measurements were done (section 7.5.2.4) to establish the suitability of the pyrolysis liquids for purposes as liquid fuel or commodity chemicals. The molecular weight provides an indication of the viscosity of the polymer, the bio-oil which mainly consists of lignin.

7.7 EXPERIMENTAL RESULTS

Taking the description of experiments and the accuracy of the fast pyrolysis yields into consideration, the following results were achieved with the biomass tested in 150g/h fast pyrolysis reactor.

7.7.1 Feedstock Characteristics and Analyses

Table 7-3 Feedstock size range and moisture contents

Feedstock	Particle Size (µm)	Average Moisture (wt.%, dry feedstock basis)
Namibian Encroachment Bush	300 – 500 and 300 - 1000	3.03
Eucalyptus	300 – 500	0.99
Black Wattle	300 – 500	12.85
Giant Bamboo	250-355 and 300 - 500	1.43

Table 7-3 describes size and moisture content of the feedstock and in Table 7-4 average analysis are presented, following various test runs and analyses.

Table 7-4 Feedstock analysis (wt%, dry basis)

	Namibian Encroacher- Bush	Eucalyptus	Black Wattle	Giant Bamboo
C	47.10	46.90	45.51	45.78
H	5.51	5.89	5.78	5.77
O (by difference)	41.88	45.60	47.73	45.50
N	0.69	0.10	0.16	0.53
S	<0.1	--	--	
A (Ash)	4.82	1.51	0.83	2.42

7.7.2 Mass Balances (yield summary)

The results for the dry wood-based biomass, the feedstock, are provided in Table 7-5. The mass balance is based on averages derived for the various test runs and subsequent analysis. The mass balance closures were good and follow the discussions presented earlier in this chapter. However, fast pyrolysis of Giant Bamboo included several disruptions due to its poor ability to feed into the reactor even though various feedstock sizes were tried. Very little to no hydrogen or C4+s were detected.

Table 7-5 Yields and Analyses (wt.%, dry feedstock basis)

	Namibian Encroachment Bush	Eucalyptus	Black Wattle	Giant Bamboo
Process Conditions				
Average fluid bed temperature (°C)	499	504	476	487
Reactor freeboard temperature (°C)	469	474	435	500
Average Vapour Residence time (s)	0.37	0.56	0.55	0.50
Yields (wt%, dry feedstock basis)				
Char	26.5	10.1	11.8	18.8
Organics	55.8	68.8	61.9	40.0
Water	10.1	11.3	8.8	16.4
Gas	8.6	10.9	14.3	14.9
Closure/Sum	101.02	101.03	96.8	90.07
Gas Yields (wt%, dry feedstock basis)				
CO_2	7.63	6.70	8.22	8.86
CO	0.59	5.17	5.34	4.89
CH_4	0.23	0.29	0.40	0.42
C_2H_4	0.05	0.09	0.09	0.05
C_2H_6	0.10	0.09	0.10	0.18
H_2	0.00	0.00	0.00	0.00
C_3H_6	0.06	0.17	0.16	0.05
C_3H_8	0.03	0.01	0.02	0.02
C_4h_{10}	0.00	0.00	0.00	0.00

The char levels in Table 7-6 are typical for woody biomass types, with the Namibian encroachment bush and Black Wattle having a lower level of C than the other biomass types presented in this research.

Table 7-6 Char Analysis

	Namibian Encroacher- Bush	Eucalyptus	Black Wattle	Giant Bamboo
C	72.0	83.4	66.8	77.6
H	2.0	2.2	2.6	1.9
O + ash	25.08	14.2	30.0	19.4
N	0.9	0.1	0.6	1.0
S	<0.1	<0.1	<0.1	<0.1
Closure	100.0	100.0	100.0	100.0

The liquids analyses in Table 7-7 are typical for wood-based biomass.

Table 7-7 Liquids Analyses

	Namibian Encroacher-Bush	Eucalyptus	Black Wattle	Giant Bamboo
C	34.2	47.0	46.2	40.9
H	8.4	7.0	7.2	9.1
O	57.4	46.1	46.6	50.1
N	0.57	<0.1	<0.1	0.1
Water content (wt%, wet basis)	7.12	12.0	12.5	11.8

No work on fast pyrolysis of Namibian and South African encroachment bush, or alien invasive plants from South Africa is known to have been carried out before. It was therefore important to establish the feasibility of fast pyrolysis and derive indicators of likely performance. The indicators presented in Table 7-6 and Table 7-7 were utilised to compute the fast pyrolysis models as presented in Chapter 8.

7.7.3 Further Product/Elemental Analysis

7.7.3.1 Additional Information for Namibian Encroachment Bush

In cooperation with VTT Finland, Namibian Encroachment Bush samples of the Cheetah Conservation Fund were tested in 2006 under the framework of the 'Feasibility Study on Electricity and Pyrolysis Oil Production from Wood Chips in Namibia'. The elemental analysis of the biomass on a percentage weight basis is provided in Table 7-8. The X-Ray Fluorescence testing (XRF) method was used to analyse the Namibian feedstock for its chemical elements. The analysis results were provided to this study for free and are mainly useful to test this feedstock's suitability in mineral reduction processes, especially for production of silicon.

Table 7-8 Elemental Analysis of Namibian Encroachment Bush (XRF Method, wt. % dry basis of feed)

Component		**Content**
Aluminium	Al	0.03
Phosphorus	P	0.05
Silica	Si	0.11
Magnesium	Mg	0.10
Sulphur	S	0.08
Chlorine	Cl	0.07
Potassium	K	0.36
Calcium	Ca	1.70
Iron	Fe	0.02
Titanium	Ti	0.006
Strontium	Sr	0.008

7.7.4 HPLC Analysis

Only Eucalyptus and Black Wattle pyrolysis oils were subjected to HPLC analysis. The results are presented in Table 7-9. This was due to financial and time constraints experienced to complete experiments on Namibian encroacher-bush and giant bamboo. Although Namibian encroacher-bush is of the *Acacia* type, it was assumed that the Namibian encroacher-bush would not render similar results as Black Wattle. Other measures provided for Namibian encroacher-bush do not come across as comparable to the Black Wattle.

Table 7-9 HPLC Analysis of Eucalyptus and Black Wattle

Name of Compound	Eucalyptus	Black Wattle
	Vol.%, dry basis	
2,3-Butandione	1.32	0.76
Hydroxyacetaldehyde	14.98	10.36
Hydroxypropanone, Acetol, Hydroxyacetone	18.83	31.37
2-Furaldehyde, 2-Furfural	7.63	7.14
2 FURANMETHANOL	1.83	2.82
(5H)-Furan-2-one	5.37	5.95
4-Hydroxy-5,6-dihydro-(2H)-Pyran-2-one	4.17	4.86
Phenol	0.89	1.91
Guaiacol	2.47	3.04
4-Vinyl guaiacol	4.30	3.90
Eugenol	0.83	0.78
5-Hydroxymethyl-2-furaldehyde	1.32	1.77
Pyrocatechol	0.59	0.75
Syringol	6.54	7.06
Vanillin	2.30	0.85
4-Vinyl syringol	2.55	2.15
Alpha-Anhydro-beta-D-glucopyranose, Levoglucosan	9.28	4.77
4-Propenyl syringol (trans)	7.26	6.70
Syringaldehyde	4.29	1.55
Acetosyringone	1.51	0.59
Coniferyl alchol	1.68	0.90

7.8 DISCUSSIONS AND CONCLUSIONS

7.8.1 Discussions

Three feedstocks, Eucalyptus, Black Wattle and Namibian Encroachment Bush, were pyrolysed with no problems during the experiments (very consistent runs with only tweaking of the reactor set point temperature to avoid over or under shooting of the furnace temperature). However, Giant Bamboo proved virtually impossible to feed. Even trying to feed two different sized fractions did not improve the situation. In all cases, blockage of the feed tube occurred even with entrain gas flows as high as 3 l/min and at low feedrates of 10 g/h and feeder top flow of 50 ml/min. To try to improve the feeding, cooling air was also fed down the annular gap in the feed tube and the feed tube exit point was moved up 5 mm more from the gas distributor in the fluid bed. It was observed that pulses of solids could be fed in by having a much higher N_2 pressure in the feeder; however this also led to blockages. The experiments auto-terminated after around 30 min. Mass balance calculations were subsequently carried out on what was attainable from the run, leading to the overall poor closure as presented in Table 7-5.

After two runs were carried out with the Namibian Encroachment Bush, which has a very high solid density of around 1000 kg/m^3, and also proved difficult to feed under the 'normal' experiment settings, the fluidising gas flow was increased from 5 l/min to 9.5 l/min and the average sand size in the bed doubled from a size range of 355-500 µm to 500-850 µm. This resulted in virtually no char remaining in the fluid bed, none in the liquids collection system and full char recovery in the char pot. In the first experiments with Namibian Encroachment Bush, a clear phase separation of the pyrolysis liquids took place in Condenser I and OP I with the biggest fraction being rather watery. The high ash content of the Namibian feedstock may have caused the phase separation of the bio-oil.

It was the first time that Southern African wood-based biomass was fast pyrolysed at Aston University. It is therefore difficult to assess whether the latter feeding problems under 'normal' settings was peculiar to this experiments set-up.

The species used to for experimentation showed similar results in terms of higher heating value (HHV) as other species occurring in Namibia and South Africa. A comparison is provided in Table 7-10. The wood species listed as per Gore [309] in Table 7-10 are derived by proximate analysis; the HHV as derived by this research are ultimate analysis.

Table 7-10 Proximate and ultimate analysis; higher heating value of Namibian and South African wood-based biomass resources [309; own research]

Species	Moisture content (%)	Ash (dry-wt.%)	HHV (MJ kg^{-1})	Specific gravity
E. paniculata	9.7	0.33	19.782	1.03
E. cladocalyx	10.0	0.45	19.190	0.87
E. saligna	10.4	0.45	19.599	0.57
***E. grandis* (own tests)**	11.3	1.51	18.923	Not tested
A. mollissima	8.6	0.44	19.213	0.86
A. cyclopsis	8.5	0.87	18.912	0.82
A. karroo	9.0	0.99	19.784	0.71
A. saligna	8.7	1.10	18.750	0.68
***A. mearnsii* (own tests)**	8.8	0.83	18.478	Not tested
***A. mellifera* (own tests)**	10.1	4.82	18.603	Not tested
P. pinaster	9.8	0.55	20.165	0.65
P. insignis	9.7	0.44	19.679	0.54
P. longifolia	9.9	0.55	19.903	0.49
P. patula	9.9	0.33	19.439	0.48
P. caribaea	9.9	0.55	21.866	0.38
***Thamnocalamus tessellatus* (own tests)**	16.4	2.42	18.485	Not tested

It would be interesting to compare the values of various wood properties of Namibian and South African species with those of wood species growing elsewhere. The unit 'National Timber Research Institute' of the Council for Scientific and Industrial Research (CSIR) which produced relevant biomass data as presented in Table 7-10 was closed down in the mid-1990s in 2007, CSIR opened the Forest and Forest Products Research Centre (FFP), a partnership with the University of Kwazulu-Natal. FFP analyses wood for its physical and chemical properties on a needs basis only; a wood properties database is not publically accessible. However, plant growth patterns generally differ from those prevailing in Namibian and/or South Africa (because of differing prevailing temperatures and rainfall). The chemical composition (and density) also differs with the age of the tree and also within the tree itself. The latter aspects make the values incomparable.

7.8.2 Conclusions

Through the experiments, the three feedstocks, Eucalyptus, Black Wattle and Namibian Encroachment Bush were found to all demonstrate characteristics suitable for fast pyrolysis, and given the analysis presented and specific thermo-chemical conversion requirements discussed in Section 7.8.1. This work will thus continue on the basis of elaborating bioenergy opportunities presented by the utilisation of specifically Black Wattle and Namibian Encroachment Bush. The biomass resources potential modelling described in Chapter 6 and the technology modelling discussed in Chapter 8, takes the experimental results offered in Chapter 7 into consideration. *Eucalyptus* is a wood-based biomass resource from commercial forestry of which there is not sufficient to warrant fast pyrolysis conversion for bioenergy (Chapter 4, 5 and 6). Therefore, the use of *Eucalyptus* species for bioenergy production via fast pyrolysis conversion will not be pursued further by this research.

The yields of the fast pyrolysis products obtained through experimentation and as summarised in Tables 7-4, 7-5, 7-6 and 7-7 are used to model the fast pyrolysis process.

8 TECHNO-ECONOMIC MODELLING OF FAST PYROLYSIS – THE BIOENERGY MODEL

This chapter describes techno-economic modelling of fast pyrolysis under Namibian and South African conditions. The information gathered and discussed in Chapters 1 to 7 on the socio-economic developments, policy and political environment, the biomass resource availability in Namibia and South Africa and technological requirements were used to build the techno-economic model. The concluding part of this chapter proposes how a relatively new technology like fast pyrolysis could succeed in Namibia and South Africa; its benefits from and challenges of introducing a new technology in the market.

South Africa essentially halted research and development for biomass processing between 1994 and 2010 [318]. Namibia only adopted research and development as part of socio-economic development initiatives in 2004 [319]. The Namibian Research and Development Act only became operational with allocation of funds to the research council in the 2011/12 budget year with the commissioning of the Namibian Commission for Research, Science and Technology [4]. The latter aspects on applied research are important to bear in mind as this research, as one objective, would propose a roadmap on how to implement fast pyrolysis technology to produce bioenergy, both in Namibia and South Africa, if fast pyrolysis is a feasible and economically viable option to pursue for bioenergy production. National support mechanisms that may be required to render infant technologies economically viable were identified and discussed in this chapter. Modelling fast pyrolysis operations assists in determining the parameters that would be required to establish a bioenergy system based on fast pyrolysis. Section 8.1 describes the parameters and models a typical fast pyrolysis process using the available wood-based biomass resources in Namibia (section 6.1) and in South Africa (section 6.2).

8.1 DESCRIPTION OF FAST PYROLYSIS OPERATIONS

Fast pyrolysis systems modelling was based on fluid bed pyrolysis, with the capacity to deliver between 1 to 20MW electricity equivalent output. The system requirements were assumed to be the same under Namibian and South African conditions. The substantial differences for fast pyrolysis in Namibia versus fast pyrolysis in South Africa were manifested in the different types of feedstock to be used. Fast pyrolysis systems in Namibia would use wood from bush encroachment only, while fast pyrolysis processes for South Africa were suggested to use wood from bush encroachment in woodlands and invasive alien wood-based plants as feedstock.

Bio-oil can be made, suitable for transport to another location (e.g. for upgrading to a fuel), or it can be used onsite for power generation as required (Figure 2-1). Most fluid bed reactors have strict particle size requirements (section 7.2); due to heat transfer limitations in large particles [320]. The feedstock was considered to be delivered as chips from conventional clearing of encroachment bush, or other chipped invasive alien wood-based plant material. For the fast pyrolysis process, the feedstock needs to be comminuted to the correct size; the cost of processing the chipped bush to fine particles was accounted for in the model. The flowsheet for the process is given in Figure 8-1 and the process unit definitions are given in Table 8-1.

A highly detailed mass and energy balance of the different types of feedstock from Namibia and South Africa was based on experimental work carried out on actual samples (Chapter 7, section 7.7.2). Conditions were optimised for liquid (bio-oil) production.

Table 8-1 Process unit definitions [68, 116] as used in Figure 8-1

No.	Description	No.	Description
C01	Wood feed Conveyors	R02	Char and Gas combustor
C02	Wood Metering Conveyor	R03	Recycle Gas Combustor
C03	Wood Feed Conveyor	R04	Excess Gas Combustor
C04	Char Recovery Conveyor	S01	Char Cyclone 1
C05-07	Char metering screws	S02	Char Cyclone 2
C08-10	Char Return Conveyor	S03	Quench Condenser
C11	Char discharge screw to storage	S04	Electrostatic Precipitator
E01	Cooling Tower	S05	Hot gas Filter
E02	Dual fuelled diesel engine	V01	Wood Hopper
F01	Air Fan 1	V02	Wood Metering Hopper
F02	Recycle Gas Fan	V03	Char Feed Hopper
H01	Air Preheater	V04	Liquids sump tank
H02	Quench Liquid Cooler	V05	Liquid Storage Tank
H03	Gas Preheater	V06	Demister
P01	Quench Liquid Pump	V07	Recycle Gas Buffer
P02	Bio-oil Pump	V08	Char and ash Receiver
R01	Pyrolysis Reactor	V09	Diesel storage tank

Based on prior work [116], the grinding of woodchips to sawdust is an expensive process on a small scale. There is a significant cost penalty for systems less than ~2 dry-t/h, as the output of electricity is virtually all consumed in the generation of electricity for on-site use. From prior analysis of feedstock preparation [102], the installation of a complete wood preparation system for small plants less than 2 t/h is not economical [116]. In most cases, purchase of a feedstock to the required specifications is cheaper, or as mentioned above, the use of available sawdust which could be sourced from elsewhere (accounted for in the South African case only). However, for this research, comminution costs were accounted for.

The commercial fast pyrolysis process is similar to the fast pyrolysis process as described under experimental conditions (Chapter 7). The commercial fast pyrolysis process commences with feedstock (wood chips) delivery. Feedstock delivered to site is stored in a 3 day buffer area. The delivered chips are then prepared as outlined in Figure 8-1. The dried ground feedstock is conveyed [C01] to the feed hopper [V01], then through an intermediate storage vessel [V02] to the biomass metering screw(s) [C02] and then in the high speed feedscrew [C03] into the fluidised bed pyrolysis reactor [R01]. The bed is fluidised using recycled and oxidised pyrolysis gases, preheated in the catalytic oxidiser [R03]. Where appropriate, a small gas burner is used to ignite the recycled gases in R03. The pyrolysis reactor is heated by means of the by-product char being combusted in an annular fluidised bed [R02], which has multiple char feed screws [C08-10], fed by metering screws [C05-07]. Char is recovered from the hot products exiting the pyrolysis reactor in cyclones [S01 and S02]. For larger scale plants, multiple cyclones would be used.

The remaining pyrolysis gases and vapours are quenched and cooled in a co-current scrubbing tower [S03], with residual aerosols removed in an electrostatic precipitator [S04]. The recovered liquids are circulated to S03, being indirectly cooled in a water cooled heat exchanger [H02], with some drawn off for storage [V05]. The liquids are then co-combusted with diesel [V09] in a dual fuel engine or engines [E02].

Residual non-condensable pyrolysis gases are passed through a demister [V06] and are then pumped by the gas fan [F02] to a gas buffer tank [V07]. The pyrolysis gases are preheated [H03] and then some are sent to R03 to fluidise the pyrolysis reactor and excess gases may be combusted in the char combustor [R02] or burnt off through a catalytic oxidiser [R04]. The hot combustion gases from the char combustor are hot gas filtered to remove char and ash particles, prior to being used to preheat the recirculation gases and preheat the air [H01] to the char combustor [R02].

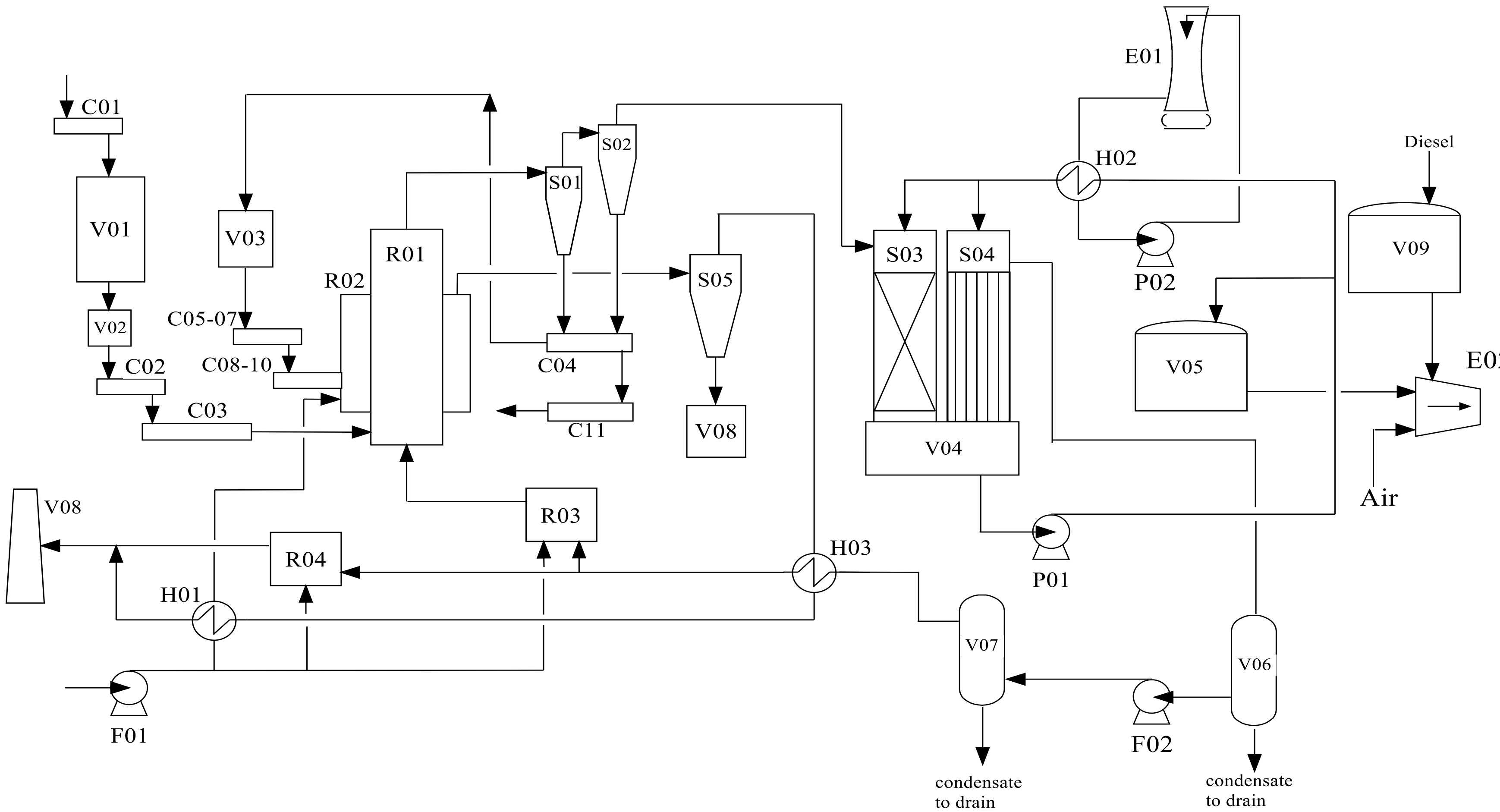

Figure 8-1 **Fluid bed fast pyrolysis with power generation in a dual fuel diesel engine [68, 116]**

8.2 BIOENERGY MODELLING APPROACH

This research focused on fluidised bed (Figure 8-1) fast pyrolysis operations which deliver an electrical output of 1MW, 5MW, 10MW and 20MW. Dependent on the electrical output required for each fast pyrolysis operation, it was important to take the following data and information into account which was presented in Chapter 5, 6 and 7:

- Feasibility testing and statutory approvals prior to operations (Chapter 4 and 5)
- Wood biomass availability (annualised, and daily) to serve as feedstock (Chapter 5 and 6)
- Compositional analysis of the biomass feedstock as well as bio-oil feedstock, including moisture and ash content of the feedstock (Chapter 7)
- Proximate and/or ultimate analysis of the feedstock (Chapter 7)
- Operational year of the fast pyrolysis plant (Chapter 5)
- Operational cost factors (Chapter 5)
- Market opportunities for the end products, both bio-oil and electricity (Chapter 6)

Other factors which influence fast pyrolysis operations and which are determined in this Chapter and Chapter 9, include:

- Desired electrical output (1, 5, 10 or 20MW)
- Engine electrical efficiency
- Diesel energy input and consumption
- Bio-oil feedstock requirements for electrical production
- Personnel requirements and availability and their cost during the operational year and day
- Capital requirements and the cost thereof are considered in the costing approach
- Technical and non-technical barriers to fast pyrolysis operations in Namibia and South Africa

Although the wood-based biomass feedstock is expected to be delivered to the fast pyrolysis operations in a chipped form, the techno-economic viability for energy production is dependent on techno-economic viability of the various individual elements in the value chain (Figure 2-1). For each component of the model, assumptions based on the literature review (Chapter 4), the conceptual model (section 2.5 and 2.6) and empirical knowledge, were integrated into each component of the model. The mathematical model and timeframe to the modelling approach are described hereafter.

8.2.1 Mathematical modelling approach underlying the bioenergy model

Following the conceptualisation of the model, a mathematical model was developed which can be described, in summary, as an optimisation model which combines social, environmental and techno-economic factors to deliver the most feasible option for fast pyrolysis of wood-based biomass. The model was solved in a spreadsheet approach (section 4.4.1) for only one objective function, i.e. maximisation of output (e.g. products or profits) under certain constraints (endogenous or exogenous). A linear programming (LP) approach was used to solve the model. The modelling approach is similar to a refinery optimisation and yield management model; and contains elements of distribution, resource allocation, blending and marketing in a multi-period setup (scheduling & assignment). Sensitivity analysis on the model can be done, for the variables. The model was analysed for sensitivity to key cost variables (biomass costs and size, some economic indicators and market prices of products). The model draws upon panel datasets compiled and generated in terms of:

- wood-based biomass resources;
- technical requirements and their cost implications;
- economic indicators; and
- market prices of products, where available.

The time frame for which the model was solved spans over a 20-year economic cycle and is directly linked to the considered harvesting cycle as presented in Table 5-4. The results of the model were presented in Chapter 9.

8.3 MODELLING OF RESOURCES IN GENERAL

Modelling of resources encompasses wood-based biomass, land, personnel and capital resources. Materials and equipment resources were accounted for under either fast pyrolysis operations or capital investment requirements. Each of these resources were shortly discussed to summarise the important aspects for modelling. The detailed discussions are provided for in preceding chapters as outlined. The descriptions below also encompass the assumptions underlying the resources model.

8.3.1 Wood-based biomass resources

The wood-based biomass resources refer to bush encroachment, under both Namibian and South African conditions; and invasive alien wooded plant species to be eradicated under the Working for Water (WfW) programme in South Africa. The biomass resources availability was determined (sections 6.1.2, 6.1.3, 6.2.3 and 6.2.4 and section 6.3). The physical and chemical properties of the feedstock were determined as described in sections 7.2, 7.5 and 7.7. Harvesting costs were considered for the wood from bush encroachment only; harvesting of invasive alien wooded plant species were considered to be covered by the WfW programme. These resources are available at source, i.e. the model takes into account that it should be transported, handled and stored prior to fast pyrolysis conversion. No third country imports of wood-based biomass were considered; neither in the raw (feedstock) form nor in the bio-oil form. If considered, these wood-based biomass resources would augment feedstock supply over the shorter term.

The cost of the wood-based biomass as feedstock were determined by solving the model. However, to prevent a circular reference while solving the model, an input value (a dummy value) for feedstock needed to be inserted. Once the breakeven value of the feedstock was established when solving the model, the dummy value is overwritten. The following dummy values for the various types of wood-based biomass were used:

- NAD100/wet-t wood from bush encroachment in Namibia; the resource is to be available in chipped form at the exit point of the farm or at biomass buffer storage sites.
- ZAR100/wet-t wood from bush encroachment in South Africa; the resource is to be available in chipped form at the exit point of the biomass harvesting site or at a biomass buffer storage site.
- zero for invasive alien wooded plant species residues obtained from the WfW programme in South Africa, at the exit point of the harvesting site. This value is also considered as the price for the resource.

The effect of biomass price on feasibility of the fast pyrolysis operations will be tested using sensitivity analysis.

8.3.2 Land Resource

Two types of land resources were considered: land on which biomass is produced and land on which the fast pyrolysis processes would take place. Land ownership for biomass production rests with farmers (Namibian case); rural communities (Namibian and South African case) and authorities (South African case). The use of wood from areas with bush encroachment makes additional land available for productive agriculture, contributing to sustained food security in Namibia and South Africa respectively. Wood-based biomass (feedstock) as required by the respective fast pyrolysis processes would be delivered at a cost at the exit of the land in question. The costs of the various feedstock were determined by solving the model. This research did not consider the harvesting and on farm transport as part of the techno-economic model, nonetheless the results of selective harvesting models were provided in Chapter 9 to determine the breakeven selling price of feedstock and test the sensitivity of fast pyrolysis operations to feedstock price. The underlying data was provided in Chapter 5.

In South Africa, the eradication and use of invasive alien wooded plant species contributes to a two-fold improved return on investment: restoration of biodiversity; and revenue generation for the parties involved. The land on which fast pyrolysis processes are to take place is considered to be bought and owned.

8.3.3 Personnel Resource

With bioenergy operations, it was expected that additional jobs would be created in Namibia and South Africa. The output from the model would determine how many additional skilled, semi-skilled and unskilled jobs will be created. Job creation positively contributes to socio-economic outcomes as desired by the Namibian and South African governments (section 2.1). It was assumed that essential training takes place relevant to the respective functions in the conversion process. Labour would be contracted on a needs basis, and availability at duty station.

Biomass resources would be bought at source; therefore labour costs and production inputs associated with obtaining the wood-based biomass resource fall outside the model. The feedstock price (section 8.3.1 and 8.3.2) was assumed to take these costs into consideration. Cost of labour, expressed as unit labour costs (ULC) and labour productivity are determined by national regulations of Namibia and South Africa respectively. The model accounts for minimum wages for unskilled and skilled labour.

The personnel requirements for fast pyrolysis processing were summarised in Table 8-2. Staffing requirements were provided for fast pyrolysis processes of the equivalent of 1 MW, 5MW, 10MW and 20MW. Please note Table 8-2 excludes staffing requirements for the electricity generation process itself; but all staffing requirements for up-stream and fast pyrolysis operations were included.

Table 8-2 Personnel requirements to operate a fast pyrolysis plant, using electrical output as measure of requirements

Duty of staff	1 MW [E] production	5 MW [E] production	10 MW [E] production	20 MW [E] production
Logistics and storage of feedstock at harvest site / conversion plant **	9	40	40	40
Chipping and milling of feedstock to correct size **	4	8	8	12
Procurement of feedstock ***	0.5	2	2	2
Sales of products ***	0.5	1	2	2
Maintenance and operations of all equipment Process Engineer* Electrical Engineer*** [E] transmission / feed-in specialist**	2	3	4	6
Maintenance Artisan***	1	1	3	5
Hourly/Shift workers **	5	5	32	64
Administration **	2	3	4	4
Overall Management ***	1	1	3	3
TOTAL	74	294	528	988

(ns=non-significant skills or technical training requirement of staff; *=weakly significant skills or technical training requirement of staff; **=strongly significant skills or technical training requirement of staff; ***=very strongly significant skills or technical training requirement of staff)

For staffing requirements as summarised in Table 8-2, the general requirements (Table 5-23) are: four-shifts per working day; 290 plant operations days per year, 40 days for annual overall maintenance and the remainder for annual and other types of leave per annum are assumed. All personnel were expected to be on site for plant operations and maintenance periods and financial (internal and external) audits.

Tasks indicated with (**) in Table 8-2, denote that prior technical training would be required to fulfil the task capably and deliver the performance needed to secure smooth operations of the fast pyrolysis plant(s). Further 'on the job training' would also be required to synchronise input and output operations.

Tasks indicated with (***) in Table 8-2, require relevant higher education with corresponding qualifications at post-graduate level and at least five years practical experience in the field of operations of a thermo-chemical conversion process.

Namibia and South Africa so far do not have any fast pyrolysis plants in commercial operation. The in-country personnel do have the technical capability to run the operations. However, all tasks denoted with (***) in Table 8-2 would require a dedicated recruitment process where talented personnel would need to be identified that can be trained to manage a fast pyrolysis plant. These employees could be recruited from operations which also run chemical conversion processes in Namibia, e.g., from the mining or food processing sector. Alternatively, skilled personnel would need to be recruited from abroad who can then work in Namibia for a limited period (subject to immigration legislation). A dedicated skills transfer programme should be engaged into by the fast pyrolysis system owners to sustain local operations. The latter was accounted for in the model by higher commissioning costs.

For the farmer, it would be more feasible to clear bush in a fully mechanised manner; rangeland rehabilitation would be accomplished relatively fast as opposed to manual cutting. However, the management of large machinery for initial clearing may be difficult to handle on the one hand, although initial clearing of land is limited to 500ha/farm/annum. On the other hand, manual clearing requires large harvesting teams to be accommodated on the farm – this is yet another challenge to overcome. In some years considerably more than the average number of workers (Table 9-4) is required to clear bush as well as to carry out the follow up and aftercare treatments. Harvesting personnel on each farm would then amount to 311 for the Okakarara and 408 for the Otjiwarongo farmland areas respectively. On average, complete manual harvesting operations delivers 6.6wet-t/worker/month of wood. Fully-mechanised harvesting operations deliver approximately 58.3wet-t/worker/month of wood. It should however be stated that fully-mechanised harvesting operations also have their limitation; bush-encroached land is not always accessible by heavy machinery due to inaccessible mountain areas, and the growth pattern of bushes itself.

8.3.4 Capital Resource

Capital is freely available on the open market at long term assumed market interest rates which are linked to the reserve banks' reposition (repo) rate. It was assumed that there would be no limitations on foreign direct investments or other capital in- and outflow restrictions and that foreign exchange legislation would not be reversed to a state where capital cannot flow freely between markets. Furthermore, the Namibia Dollar (NAD) would remain pegged to the South African Rand (ZAR) over the forecast period. The long-term foreign exchange rates between hard currency (USD, GBP, EUR) and NAD and ZAR respectively are difficult to track and were assumed to follow depreciation/appreciation as per inflation movements. Over the modelling period the long term exchange rate was assumed to be as per Table 5-23. Other capital related economic indicators were provided for in Table 5-23 too. It was assumed that sufficient operating capital would be available for fast pyrolysis operations, i.e. no overdraft facilities would be required or taken. Overall capital cost is a function of the operations carried out in the project and is case and location sensitive.

8.4 HARVESTING, LOGISTICS, TRANSPORT AND STORAGE OF BIOMASS RESOURCES

Harvesting of biomass would commence at least three months prior to commissioning of the fast pyrolysis operations. Feedstock supply to a central buffer storage points would commence one month prior to commencement of fast pyrolysis process until the 3-day buffer storage would be reached at optimal moisture content levels. Storage of feedstock would be in the form of wood chips. This would save costs of bulk feedstock preparation and transport.

Although harvesting was not part of the fast pyrolysis model, there would be a requirement by the project that harvesting methods comply with national regulations (Table 4-5) [321]. It was assumed that all biomass feedstock suppliers continuously abide by these and comply with environmental laws and standards at all times, including renewals of certificates when/where required.

In Namibia, fast pyrolysis operations were assumed to take place in Otjiwarongo and would cater for biomass from the Okakarara and Otjiwarongo farmland areas (section 6.1.3 and 6.3). In South Africa, three fast pyrolysis operations were considered: one in the Eastern Cape, one in the Western Cape and one in Gauteng Province. The cost of transport and logistics of biomass as feedstock to the fast pyrolysis plants were indicated in Table 5-22. The cost of transport may render fast pyrolysis operation not economically viable if the distance between locations of the wood-based biomass resource and the fast pyrolysis conversion site is further away than 200km. Thus, buffer biomass storage sites are assumed. This would allow suppliers of biomass to deliver smaller loads of chipped feedstock to such site. The buffer biomass feedstock sites would serve a dual purpose: larger loads of chipped feedstock can be delivered to the fast pyrolysis conversion site at lower cost just-in-time; and storage holding space and cost at the fast pyrolysis conversion site can be optimised.

A 3-day feedstock inventory at the fast pyrolysis conversion site is assumed. Feedstock in the form of wood chips is to be stored at the conversion site. Comminution or grinding of woodchips would take place as feedstock enters the conversion process. The size of the feedstock for conversion should be even sized, i.e. maximum 1 mm diameter and 5 mm length.

Moisture content for all feedstock is crucial. Moisture content of feedstock would be measured twice; first prior to storage and then before conversion. All feedstock entering any of the above listed conversion processes were assumed to have a moisture content on a weight basis of equal or less than 18%. Maximum tolerable moisture content would be less than 20% on a weight basis. High moisture content or large variations in moisture content between wood particles negatively influence the quality of the final product. It was assumed that storage facilities for feedstock are appropriately and sufficiently ventilated. The Namibian and South African climatic conditions allow for feedstock to be air-dried in areas protected from rain and being well ventilated. However, during certain times of the year air-drying may not be possible. Therefore, additional feedstock drying equipment would be required (Figure 8-1). Inappropriate feedstock storage facilities induce degradation of feedstock prior.

Storage costs for biomass feedstock were assumed to be less or the same as biomass resource costs and should not exceed the cost of the resource. Maximum tolerable feedstock preparation costs for the fast pyrolysis conversion process would be determined by solving the overall model. The costs were limited to grinding wood chips to desirable size directly before conversion.

8.5 MODELLING OF FAST PYROLYSIS OPERATIONS

Modelling of fast pyrolysis took account of the products derived from the process, with process settings determined to maximise bio-oil yield. Products from fast pyrolysis yield charcoal in powder form, bio-oil (liquid extracts) and incondensable gas, all with their resultant properties. Product yields for a specific wood-based biomass were determined and the results were presented in Chapter 7.

Fluidised bed processing as per experimental work (Chapter 7), and existing pilot and/or commercially available technology and cost structures (section 8.1) were consisered. Equipment and parts costs were obtained from suppliers of the equipment, some of them operating in Namibia, others in South Africa. For the fast pyrolysis reactor, equipment and components were assumed to be imported from Europe and/or the USA, attracting high costs due to payments necessarily to be done in hard currency. Emphasis was placed on the primary fast pyrolysis conversion process, i.e. conversion of wood-based biomass into bio-oil. The downstream production of electricity was only accounted for in the model to determine the production price of electricity. This is because authorities require that the provider of such electricity should also install the transmission infrastructure to the nearest transformer station or distribution hub. The latter is outside the scope of this research.

The production price for electricity was determined to compare it with proposed statutory renewable energy feed-in tariffs (REFIT). If electricity production via fast pyrolysis would more expensive than REFITs (section 5.5 and 5.6), fast pyrolysis processing of wood-based biomass may not be economically viable; or operational cost savings would need to be investigated; or in the worst case scenario, REFITs as proposed may have not accounted for all cost factors while introducing a new energy production system at a national basis. The sensitivity analysis would assist in identifying cost factors that would require re-consideration.

8.6 LOGISTICS, HANDLING AND TRANSPORT OF BIO-OIL

Bio-oil production was considered to be the main purpose of fast pyrolysis conversion of wood-based biomass in Namibia and South Africa. Bio-oil would be used for the production of electricity on site as per Figure 8-1. Both, on-grid and off-grid electricity production were considered to be feasible and thus warranted further investigation. Only excess bio-oil would be stored and/or sold to other markets, either inside or outside Namibia and/or South Africa. Bio-oil is handled, stored and transported according to international standards. The technical standards for bio-oil handling are as follows [322, 323]:

8.6.1 Bio-oil handling, storage and transport

All bio-oil wetted surfaces should be of Stainless 304, 316, HDPE, EPDM, PVC or Teflon drums because of bio-oil's acidity (pH of 2.2 - 3.0). During storage and transportation bio-oil should be kept above 15°C to maintain good fluidity, but should not be stored at temperatures higher than 40°C for long periods to avoid polymerisation. During storage bio-oil should be agitated or circulated to maintain good homogeneity. Bio-oil does not exert pressures at temperature much different from water. Carriers designed to handle diesel fuels or similar products would suffice also for bio-oil.

For pumping large quantities of bio-oil (more than 10t), all piping must be large enough and not less than 75mm (3 inches) diameter on suction (keeping it as short as possible with a generous net positive suction head 'NPSH') and with a 50mm (2 inch) diameter on discharge-use reinforced PVC hose if practical.

8.6.2 Cleaning bio-oil out of tanker and cleaning agents for bio-oil

Cleaning is best done with denatured ethanol. It will depend on end user requirements of the bio-oil but it may be possible to add the collected wash spill to the bio-oil, in particular if the end use is as a fuel. The tanker should not be washed with water as it will cause separation. Ethanol is preferable to methanol. The carrier is advised to carry a small amount of denatured ethanol with him to clean tools and valves.

Denatured ethanol (recommended) and methanol are both good cleaning agents for bio-oil. However, as the latter are also hazardous materials their use should also be guided by their materials safety and data sheets (MSDS) information. Ethanol and methanol are poisonous and combustible. Bio-diesel in industrial applications has proven to be a good cleaning and solvent agent.

8.6.3 Cleaning of bio-oil spills in water

Unlike with oil spills, bio-oil being heavier in water will quickly sink to the bottom where much of it will dissolve with time (up to 65%). Parts of bio-oil are water-soluble [322, 323].

8.6.4 Bio-oil and other fast pyrolysis products' production price structure for modelling

No market value for bio-oil exists in Namibia and South Africa. Charcoal does have a market value; however, that is for lumpy/solid pieces of charcoal produced from slow pyrolysis processes. Fast pyrolysis delivers a charcoal in powder form and thus the model assumed that charcoal is a co-product used in process as source of heat. The breakeven selling price of bio-oil derived from fast pyrolysis conversion processes would be determined by solving the model. The breakeven selling price for bio-oil would be calculated based on all input costs.

The market value for producer gas obtained from the fast pyrolysis gas is not known. It is therefore assumed that renewable energy feed-in tariff for biogas under the South African governments' renewable energy programme for the generation of electricity is also valid for pyrolysis process gas should a possibility arise to sell this. The suggested price applied for costing bio-oil under South African conditions is ZAR0.96/kWh equivalent [296] (Table 5-28).

8.7 MARKET RELATED ISSUES CONSIDERED BY THE BIOENERGY MODEL, PARTLY ALSO REFERRING TO POLICY MEASURES

The aim of this research was *inter alia* to analyse the opportunities of bioenergy production for socio-economic development in Namibia and South Africa. This means, marketing of bioenergy was determined by the demand for and the possibility of on-grid feed-in of electricity produced by using bio-oil as fuel for electricity generation. Potential was also based on future supply of wood-based biomass resources. Renewable energy production is currently supported by conducive national policies and regulations in Namibia and South Africa. However, the policies and regulations in place do not specifically mention bioenergy production via the fast pyrolysis route. The policies mention bioenergy from "biomass and biogas" (Table 5-26 and Table 5-28) though. Thus, bioenergy via the fast pyrolysis route seems not to be specifically excluded. It was therefore assumed that national policies, procedures and regulations are also applicable to bioenergy production via fast pyrolysis, and would pertain to the following:

- The respective industrial policy of Namibia [6] and South Africa [289];
- For Namibia REFITs, tariffs as per Table 5-26 apply
- For South Africa, the biofuels strategy and directive [7], and proposed feed-in tariffs for electricity (Table 5-28) apply
- Renewable Energy Technology accreditation procedures and standards (Chapter 9.9)
- Market and product standards are determined by the Namibian and South African authorities, for example –
    - Namibia: Ministry of Mines and Energy (bio-oil standards); Electricity Control Board (electricity generation based on bioenergy);
    - South Africa: South African National Standards (bio-oil standards); National Electricity Regulator of South Africa (electricity generation based on bioenergy).

In terms of bio-oil an existing market is lacking. The model assumed that all bio-oil would be utilised for electricity production on site where fast pyrolysis takes place. However, with time there may be surplus supply. Any surplus supply was assumed to be sold at NAD or ZAR0.50/l ex-factory. This is the indicative price for wood-tar from the AGODA process as sold in 2008.

8.8 SOCIAL AND ENVIRONMENTAL IMPACT AND SUSTAINABILITY

Constraints to the model are driven by national policy and regulation with regard to

- National [286, 125, 179] and international sustainable development objectives, standards and agreements, notably the Kyoto Protocol [240];
- National health and safety regulations [324, 325]
- International voluntary standards on social responsibility and labour / employment measures [326].

Choosing biomass to generate additional energy capacity for Namibia and South Africa bears greenhouse gas emissions abatement potential [66]. The potential was assumed to be materialised through CO_2-income at ZAR150/CO_2-t. However, optimisation of the model does not consider income from CO_2 as a first option as the trading possibilities with CO_2 in Namibia and South Africa are limited. The trading framework has caveats and the likelihood to obtain CO_2 trading license in both Namibia and South Africa is very limited.

Additional governmental fiscal and tax-based subsidies were not considered. However, such may turn an otherwise less feasible and economically less viable bioenergy generation investment into a profitable one.

Any new fast pyrolysis conversion systems and corporate entity to be built in Namibia and South Africa is required to integrate sound environmental practices, labour practice and social responsibility into its business model.

8.9 MAIN ASSUMPTIONS UNDERLYING THE BIOENERGY MODEL FOR NAMIBIA

8.9.1 Biomass resource use; feedstock supply and security of feedstock supply

Although potential may exist to source other types of biomass resources (dung, municipal waste, agricultural production waste) in Namibia, these have not been taken into consideration. The bush inventory at hand and annual bush growth rate for the Okakarara and Otjiwarongo farmland areas respectively was provided in Table 5-15 and were considered to be sustainable to continuously supply feedstock to fast pyrolysis operations. The wood harvesting cycle coincides with 20-year bioenergy modelling period. Any future use of wood from bush encroachment for fast pyrolysis would not compete with any current or future residential and industrial use of the same resource.

Farmers would harvest and supply bush to fast pyrolysis operations under supply contracts. The bush would be bought directly from the farm owners. Targeted government interventions for bulk harvest and supply of bush would be limited to government owned farms and communal farming areas, as may be the case for the Okakarara farmland area. In addition, buffer or bulk feedstock storage sites would be put up (section 8.4). To sustain supply, renewable 3-year contracts would be agreed upon with farmers, stipulating the annual amount of supply, and were assumed to be in place before operations commence.

8.9.2 Costing approach

The base case cost was taken as the breakeven price of the biomass (in NAD per wet-t) delivered in bulk to the farm gate or the bulk storage site. Transportation of bulk biomass or the wood chips is not further than 100km from the fast pyrolysis site. The wood chips are produced from bush encroachment and consist mainly of bush trunks, disbranched and no leaves (i.e. TE-units). It was assumed that wood would only be harvested from bush encroachment and according to regulatory requirements [321]. Harvesting schedules (Table 5-4) served to assess the socio-economic and environmental impact of wood utilisation from bush encroachment.

All other cost indicators required for bioenergy modelling were provided under section 5.3. The costing approach for fast pyrolysis operations is described hereafter.

In the course of the techno-economic assessments and deriving the relevant cost information, consistency in the approach for comparisons was provided for as suggested by the "black box" approach (section 4.4.3). To determine individual cost items, the factorial estimation methodology was used. For the fast pyrolysis and each of the clearance options noted above, the following basic parameters were set:

- Capital cost was calculated as total plant cost (TPC), including both direct and indirect costs.
- Maintenance and overheads was calculated as a percentage of TPC.
- The following financial scenarios have been considered:
  - 100% loan and 0% equity
  - 75% loan and 25% equity
  - 0% loan and 100% equity
- Production costs were estimated based on annual operating costs and the net electrical output.

- The profitability analysis was based on nominal (influenced by inflation) discounted cash flows.
- The following formula was used for the calculation of the discount rate
  Discount rate = Debt ratio x Interest rate + Equity ratio x IRR on equity = 14% at 75:25 ratio for 12% interest rate and 20% return on equity
- A 20% internal rate of return [IRR] on equity was assumed for the determination of average bio-oil price over the lifetime of the plant.

Costs associated with the production of bio-oil, comprise an annual cost of capital (assuming all of the capital was loaned), to which the annual operating costs of the plant were added. The operating costs comprise feedstock cost, labour, utilities, maintenance and overheads. The cost of electricity was obtained by summing the production cost elements, and dividing by the total annual production of electricity. The methodology for calculating each of the production cost elements was described in section 8.9.3.

8.9.3 Capital Cost estimation

Capital cost was calculated as a total plant cost, which includes both direct costs (installed equipment) and indirect costs (engineering, design, supervision, management, commissioning, contractor's fees and interest during construction, contingency).

The validity of any model can only be confirmed by comparison with actual cost data for installed plants. This was difficult in the Namibian and South African situation as no fast pyrolysis plants exist (section 4.3.1). Comparative costs from Europe were used instead. Where possible information was obtained from plant manufacturers or owners, or other published data. Information established by setting up a database over time was also used. Own prior work carried out on the techno-economic assessment of bioenergy systems was found to correlate closely with industry costs for most of the options costed in this research.

Based on the duration of the project, equipment cost and unit operation costs were used to compile the capital costs estimation over the long term; these can more easily be updated with a cost index over longer periods than a five year horizon mentioned by Gerrard [327].

8.9.3.1 Total Plant Cost [116]

Total plant cost *[TPC]* was built up in the following manner:

The delivered cost of each process unit as purchased or as obtained and the final installation cost based on actual costs from industry (by obtaining quotations) or calculated costs. Various items related to installation were then added to the equipment cost (*EC*) to give the direct cost for each process unit. This was done using direct cost factors published by the UK Institution of Chemical Engineers [327]. The factors can take the form of the equation below.

Equation 8-1 Final installation costs

$$\mathbf{F} = \mathbf{c}(\mathbf{aEC^b})$$

Where:

> *a* and *b* were constants for a given factor, and *c* was a multiplier to be included if unusual or atypical conditions pertain. Factors were applied for piping, instrumentation, lagging, electrical, municipal installations, structures and buildings. The direct cost [*DC]* was then calculated as per Equation 8-2.

Equation 8-2 Direct costs for plant installations

$$\mathbf{DPC} = \mathbf{EC}(\mathbf{1} + \sum \mathbf{F})$$

The direct costs were added to give the direct plant cost (*DPC*). Indirect costs were then added to give *TPC*. This was undertaken using factors published by Bridgwater [328] and Gerrad [327].

8.9.3.2 Operating Cost Calculations [116]

For the operation of the system, staff requirements were adjusted to commercially operate the system for continuous operation on a 4 shift pattern (3 on, 1 off). The components of the operating cost were: annual cost of capital, labour, utilities (electricity and water), maintenance and overheads. The system was assumed to be automated as much as possible as would be the standard industrial case.

8.9.3.3 Capital Amortisation and Depreciation [116]

Capital was amortised using the standard relationship [329] and further simplified since the equipment used is likely to have different working lives and some items may need replacing during the life of the project. A fixed charge was accounted for to take account of equipment replacement during the lifespan of the conversion system, which was assumed to be the same magnitude as costs of spare parts.

For depreciation, the allowances granted by the Namibian and South African governments are similar and were taken into consideration, i.e. 20% of capital employed in the first year in which the plant and equipment has become operational, and thereafter 8% for the next consecutive 10 years.

8.9.3.4 Utilities

Only utility requirements for continuous operation were taken into account; any start-up requirements were ignored. The two utilities considered were electricity and water and these were based on the operational experience and from estimates obtained from the overall mass and energy balances for each process.

8.9.3.5 Electricity

In a complete electricity production plant, the electrical power necessary to operate the plant would be taken from the gross output from the generator terminals prior to the point of connection to the customer.

For "Greenfield" investments in fast pyrolysis operations, especially those to be located in rural areas or on commercial farms, electricity supply would come from system itself. Cost for building transmission lines for the electricity to be fed to the national grid may have to be considered. The national power company usually does not provide this to independent power producers, in both Namibia and South Africa. These costs have not been considered by this research as it falls outside the main objective of the research subject.

8.9.3.6 Water

Water requirements are for make-up water for the cooling tower of the fast pyrolysis systems respectively. Bulk water supply is required for replacement of cooling water losses from cooling towers; costs thereof were shown in Table 5-24. Any recovered condensate from gas cleaning operations is sent where possible to drain, or used for onsite irrigation (if appropriate, i.e. condensate meets emission requirements in terms of contaminants). However, it should be noted here that under Namibian conditions it may happen that the owner a fast pyrolysis operation in the "Greenfield" would have to provide for his own water supply. This is especially the case when a fast pyrolysis plant is to be established in rural areas or on a commercial farm. Water in this case is usually sourced from boreholes.

8.9.3.7 Maintenance and overheads

Maintenance and overheads were both included as a fixed percentage of TPC per annum. Values for the overhead and maintenance rates were taken as averages for a range of industries in Namibia and South Africa. A typical value of 7% was used. It can be argued whether 7% is sufficient in the context of introduction of new technologies like fast pyrolysis. Experience has shown (Chapter 2, section 2.1, 2.3, 2.4 and 2.6) that 10% may be more appropriate.

If the fast pyrolysis plant is to be located in a rural area or on a commercial farm, no ash disposal costs become necessary. Ash could be reintroduced to rangelands as soil ameliorant where livestock is frequently roaming or resting.

8.9.3.8 Working Capital Requirements

This cost factor was calculated as 30% of the capital cost estimate [327]. An additional cost factor of 10% was assumed for challenges possibly to be encountered due to the introduction of a new technology into Namibia and South Africa (Chapter 2, section 2.1, 2.3, 2.4 and 2.6).

8.10 MAIN ASSUMPTIONS UNDERLYING THE BIOENERGY MODEL FOR SOUTH AFRICA

8.10.1 Biomass resource use; feedstock supply and security of feedstock supply

Two options were considered for available wood-based biomass in South Africa, i.e.:

- Wood from bush encroachment in mainly woodlands; the resource grows at a rate of 2.5% per annum and the amount of wood assumed to be available is 29.7 Mwet-t (Table 5-16); this resource will be harvested from the Limpopo, Mpumulanga and Northwest Provinces.
- Invasive alien wood-based plant species as occurring in the Eastern and Western Cape – the assumed amount of wood-based biomass available is 12.9 Mwet-t per annum (Table 5-16), but declining over the next 20 years or until its full eradication is achieved.

To source wood from bush encroachment in woodlands, private farmland owners would harvest and supply biomass in a chipped form to a central location. Targeted government interventions for bulk harvest and supply of invasive alien plant species are assumed. Fast pyrolysis systems owners were assumed to collect and transport the biomass resource to conversion sites.

For all biomass supply chains in South Africa contracts with potential suppliers are essential.

To sustain supply, 3-year renewable contracts, stipulating annual amount of supply were assumed to have been agreed upon. Supply of biomass should start three months before commissioning of fast pyrolysis operations to establish and maintain the 3-month inventory level due to the distances to be covered between harvesting and conversion sites.

8.10.2 Costing approach

The cost structure for South African wood from bush encroachment was assumed to follow the Namibian example. Wood as harvested from clearing alien plant species through the Working for Water (WfW) programme are residues and assumed to be chipped to technical specifications, and would be free of charge in line with the policy objective of the programme (section 4.1.5). Collection of the feedstock and storage at conversion site were considered to follow market rates of similar commodities at ZAR10/wet-t.

All other cost indicators required for bioenergy modelling were provided under section 5.4; except for land costs which differ considerably from Namibia (section 5.4.3.1), were as indicated in specifically sections 5.3.3.2 and 5.3.4; the costing approach for South African fast pyrolysis operations were described in sections 8.9.3.

8.11 EQUATIONS USED FOR MODELLING

8.11.1 Resource availability

Total resource availability has been established in section 6.1.2 (for Namibia) and section 6.3.1 (for South Africa), consequently the results obtained will be used.

8.11.2 Cost of biomass resources

A base case cost for the biomass resources is assumed as per sections 8.9 and 8.10. However, the cost of the biomass resources needs to be established and is equal to the breakeven selling price of the resource. Determining the breakeven feedstock selling price assists to optimise pricing for this resource and is expressed as:

Equation 8-3 Cost of resources

$$\boldsymbol{\lambda} = \mathbf{p} - \mathbf{c}'(\mathbf{h}, \mathbf{d}, \mathbf{g}, \mathbf{s}, \mathbf{dry})$$

Where:

p is the breakeven feedstock selling price (NAD or ZAR/wet-t) at farm gate/resource location (if valued or costed), and c’ was calculated using Equation 8-4.

Equation 8-4 Establishment of c', the sum of harvesting, transport, grinding, drying and storage costs

$$\mathbf{c_j} = \sum_{j}^{n} [(\mathbf{h_j} + \mathbf{d_j} + \mathbf{g_j} + \mathbf{s_j} + \mathbf{dry_j})(\mathbf{1} + \boldsymbol{\pi})^{\mathbf{n}}]$$

Where:

h is the additional marginal harvesting and feedstock preparation cost on farm prior to delivery to the fast pyrolysis conversion or the buffer storage site (if any),
d is the transport distance charge for each resource type j in NAD or ZAR/km,
g is the grinding or feedstock preparation cost,
s is the storage cost (only considered where stockpiling is necessary for security of supply),
dry is the drying cost for feedstock with moisture content above 20% on a weight basis; and π is the assumed inflation rate in percent (%).

Distance charges are scaled according to kilometres to be transported, with a maximum transport distance of resources to the fast pyrolysis operation of 100km in the Namibian case and 200km in the South African case. The marginal cost or breakeven value of the feedstock (p) would be determined by solving the model. To prevent the solving of the model to revert to a circular reference, a dummy value for feedstock had to be assumed; in this case e.g. NAD or ZAR100/wet-t. The cost of feedstock was upper-bound to NAD or ZAR300/wet-t, after which it was considered to become unfeasible to use a certain resource type j for fast pyrolysis.

8.11.3 The fast pyrolysis conversion processes under review

This section deals with the second objective function, i.e. the assignment of biomass resource (feedstock) to a fast pyrolysis plant with an assumed electricity output of 5MW in relation to the first objective function and factors of production, like labour force available, technological and economic suitability. A 5MW electricity output was chosen as the initial step. Depending on the availability of wood-based biomass resources for the chosen sites, the electricity output capacities would be adjusted to either 1, 5, 10 or 20MW for each site, as desired. The feasibility of each electricity output capacity was be tested. All fast pyrolysis processes would use a fluidised bed system (section 8.1). The feasibility and economic viability is benchmarked to a 5t/h fast pyrolysis operation. Should additional installations of fast pyrolysis become feasible and economically viable, it was considered that first the replication of the equivalent electricity output would be installed, before the next bigger fast pyrolysis conversion option would be suggested for feasibility and economic viability testing. All fast pyrolysis conversion processes were considered to be Greenfield investments. As this research specifies the need to only test feasibility and economic viability of fast pyrolysis for heat, electricity or fuel production (not chemically valuable components), all resources were allocated as discussed in sections 8.3, 8.4, 8.9 and 8.10.

The model is capable to assign resources to a specific pyrolysis process at a certain site and matched to the desired electricity output capacity. For Namibia, only one fast pyrolysis site was earmarked, that is in Otjiwarongo; for South Africa, three fast pyrolysis sites were earmarked respectively (Eastern and Western Cape, and Mpumulanga Province).

The first fast pyrolysis option to be tested would have a capacity of up to 5t/h air-dried feedstock intake, and would therefore produce bio-oil (prod6), producer gas (prod4) and recovered gas (prod5) charcoal (prod1) in the amounts determined by experimentation (Chapter 7). The other fast pyrolysis options were tested in a similar manner. The following equation for modelling a 5t/h fast pyrolysis process holds:

Equation 8-5 Total production costs per tonne of bio-oil in the fluidised bed fast pyrolysis system

$$\mathbf{3.59x_j + 3.8L + 97.5K - \omega - 283 \geq 0}$$

Equation 8-6 Total annual production capacity per 5MW-equivalent reactor size, and where maximisation of bio-oil production ($prod_4$) is the proxy

$$\mathbf{prod_i x_j + \omega - 23044 \geq 0}$$

Where:

The sum of $prod_i x_j$ is equal to 1 as determined by fast pyrolysis experimentation (Chapter 7). The ratios in which the products ($prod_i x_j$, that is char, gas (producer and recovered gas) and bio-oil) occur are e.g. $prod_1 = 0.138$; $prod_2 = 0.055$; $prod_3 = 0.055$; $prod_4 = 0.752$ for e.g. Namibian encroachment bush was used as feedstock.

The constant 23,044 represents the amount of annual feedstock capacity intake for a 5t/h fast pyrolysis plant.

- $prod_1$ is product1, i.e. charcoal produced, by fast pyrolysis; $prod_1$ is internally combusted as fuel for the fast pyrolysis process;
- L is hours of operation (composed of labour (lab) and technical (tech) availability; denoted as a ratio of total operational hours available) as per Table 5-22;
- K is capital requirements in NAD or ZAR (convertible to hard currency when necessary)

as described in section 8.9.3;

- ω is the wastage/start-up feedstock/by-products from the process (to be minimised); and x_j, L and K ≥ 0.

The fast pyrolysis production system has the following boundaries:

- (lab + 0.8tech)L ≥ 7008 operational hours (Table 5-22), divided into shifts, per annum; this represents 80% of total annual hours for plant availability to produce 5MW electricity continuously
- K is composed of cost and economic indicators as per Table 5-23 and Table 5-24, as well as indicators of the costing approach as outlined in section 8.9.3
- δ ≤ 150 (feedstock diameter in mm)
- β ≤ 1,500 (feedstock length in mm)
- MC ≤ 0.2 (feedstock moisture content on weight basis less than 20%)
- Ω ≥ 20 (technical life span of conversion equipment in years, after which capital replacement is necessary).

8.12 BENEFITS

The benefits of clearing bush encroachment or alien invasive plant species were considered to be eminent from:

- total land area cleared (ha or Mha)
- improved rangeland conditions, thus improved carrying capacity and livestock production output (g or kg (live body mass)/ha)
- improved biodiversity, where total land area would be used as proxy
- additional employment created through harvesting of wood-based biomass and through pyrolysis operations; and
- other macro-economic gains, like additional GDP.

The measures applied were considered as follows:

- actual lessening of spatial spread of bush encroachment (ha) and its density (possible yield expressed as t/ha) (Table 6-3 and Table 6-4)
- actual lessening area invaded by A. mearnsii in the Eastern and Western Cape respectively (Chapter 9)
- number of additional jobs, skilled and unskilled created (Table 5-20, Table 9-1, Table 9-2,

Table 9-3)

- monetary amount of possible additional taxation income, capital formation and output to the primary (agriculture) sector generated by the total value chain of bioenergy generation
- total amount of the population sustainably supplied with electricity on an annual basis.

The results of benefits per fast pyrolysis output capacity (1, 5, 10 or 20 MW equivalent) were presented in Chapter 9.

8.13 SUMMARY

In the Namibian case, fast pyrolysis process modelling considered one site, that is, Otjiwarongo-town, for biomass to bio-oil conversion, but four different outputs, sourcing the wood-based biomass from multiple sites in the Okakarara and Otjiwarongo farmland areas. Feedstock supply was assumed to be sourced under contractual arrangements between the farmer harvesting and delivering it, and the fast pyrolysis plant owners.

In the South African case, fast pyrolysis modelling considered three sites at which biomass could be converted to bio-oil, that is, in the Eastern and Western Cape, and in Mpumulanga Province respectively. Feedstock for the fast pyrolysis plants in Eastern and Western Cape would be derived from wooded alien plant species to be eradicated according to the 'Working for Water' programme. Feedstock for fast pyrolysis operations in Mpumulanga Province would be derived from bush encroachment occurring in Limpopo, Mpumulanga and North-Western Province. Mpumulanga Province was suggested as the conversion site due to central geographic location as well as the availability and density of existing energy infrastructure within the areas identified as bush encroached.

The objective of the fast pyrolysis process would be to produce bio-oil for electricity, heat or fuel. The capacity of the fast pyrolysis plants was modelled to an equivalent of 1, 5, 10 or 20 MW electrical output. Feedstock and bio-oil were considered to be transported not further than 100km in the Namibian case and 200km in the South African case due to high transportation costs. A dummy feedstock price was used (NAD or ZAR100/wet-t) to enable the computation of the breakeven feedstock price. Feedstock was considered to be delivered in chipped form with a moisture content of ≤20% to the fast pyrolysis conversion site. Conceptual and mathematical models were presented to derive the breakeven selling prices for feedstock, bio-oil and electricity. The models were solved using the presented equations in a spreadsheet approach.

9 RESULTS OF BIOENERGY MODELLING

This Chapter presents the results of bioenergy modelling in Namibia and South Africa. The first part of the Chapter (section 9.3, 9.5) presents the results of bioenergy modelling, while the second part (section 9.6) provides an overview of the technical and non-technical barriers to fast pyrolysis operations in Namibia and South Africa.

The description of the bioenergy models was presented in Chapter 8. With the different types of biomass and technology in mind, various costs and benefits were taken into consideration to test the feasibility and economic viability of fast pyrolysis for bioenergy production in Namibia and South Africa. Namibia has one wood-based biomass resource available for fast pyrolysis conversion; South Africa has two economically viable wood-based biomass resources available for fast pyrolysis conversion.

Fast pyrolysis is presented as a greenfield investment. It was therefore useful to compare the results to existing fast pyrolysis operations elsewhere, e.g. in Europe or the USA. The latter was considered important in view of technology and know-how transfer required, bio-oil price competitiveness testing and market diversification. Comparison to existing operations also assisted to counteract doubt or suspicion in Namibia and South Africa to *why and how* a new technology could/should be introduced into these countries. The matter was discussed in Chapter 10.

9.1 SUMMARY OF NAMIBIAN SCENARIOS CONSIDERED FOR MODELLING

In the Namibian case, techno-economic assessment included various harvesting options for the encroacher-bush to determine the breakeven selling price for the wood resource delivered at the farm gate. The scenarios assessed under which conditions the encroacher-bush could be supplied, were based on a harvesting level of 500ha per farm per year of an average farm size of 5000ha from some 50 communal (non-freehold) farms in the Okakarara and 600 commercial (freehold) farms in the Otjiwarongo farmland area. The harvesting options for which a feedstock breakeven selling price was determined are:

- Complete manual operations, aided by pangas (a type of machete) and axes only; chipping of wood would still be required and would attract additional costs for feedstock preparation.
- Fully mechanised harvesting, compilation and chipping to size of wood ready for transport to the buffer storage or fast pyrolysis conversion site.

Cost of transport of the chipped feedstock from the farm gate to the buffer storage site and/or fast pyrolysis conversion site is additional to the costs of fast pyrolysis conversion.

The options to test the feasibility of fast pyrolysis conversion for bioenergy production were considered based on a 20-year investment and operational cycle. The breakeven selling prices for feedstock based on harvesting models were calculated. The fluidised bed pyrolysis conversion processes assessed included:

- 1 t/h feedstock intake;
- 5 t/h feedstock intake;
- 10 t/h feedstock intake; and
- 20t/h feedstock intake.

All costs and benefits were presented relative to the sustainable supply of feedstock, thus rendering the most feasible and economically viable option of a fast pyrolysis conversion processes for bioenergy generation. Only wood from bush encroachment as feedstock under Namibian conditions was considered. The feedstock would be supplied combined from the Okakarara and Otjiwarongo farmland areas. The fast pyrolysis conversion operations would be located at Otjiwarongo; bio-oil for power generation is the primary product, and thus power would be supplied to the national grid at 'Gerus'. Off-grid power generation and distributions would also be a possibility. The breakeven selling price for bio-oil and then per unit power produced was determined by solving the bioenergy model.

9.2 SUMMARY OF SOUTH AFRICAN SCENARIOS CONSIDERED FOR MODELLING

In the South African case, two types of biomass were assessed for their suitability as feedstock for fast pyrolysis conversion at three different locations. The types of feedstock are processed at the following locations:

- Wood from bush encroachment in woodlands; the fast pyrolysis conversion site was suggested to be located in Mpumulanga Province due to its central location within the bush-encroached area and the existing energy infrastructure; and
- Invasive alien wood plant species from and processed in the Eastern and Western Cape respectively.

Similar to the Namibian case, costs of harvesting biomass from bush encroachment were determined by establishing the breakeven selling price of the wood-based biomass as feedstock. The price of feedstock from alien wood plant species was assumed to be zero, because clearing of the sites would already have been accomplished by the Working for Water interventions.

The feasibility of fast pyrolysis conversion options to deliver bioenergy was considered based on a 20-year investment and operational cycle. All costs and benefits were matched to the sustainable supply of feedstock, thus rendering the economically most viable option of fast pyrolysis conversion for bioenergy generation. The fluidised bed pyrolysis conversion processes assessed include:

- 1 t/h feedstock input; and
- 5 t/h feedstock input.

By solving the bioenergy model, it was determined that feedstock supply in the South African case does not warrant erecting fast pyrolysis plants beyond a 5t/h feedstock input capacity (section 9.5).

9.3 TOTAL PERSONNEL REQUIREMENTS

Under socio-economic considerations, personnel requirement is a function of harvesting methods and capacity of the fast pyrolysis conversion process, expressed in equivalent of power output. Complete manual labour harvesting operations combined with the highest capacity of fast pyrolysis conversion process requires the most personnel. The skills level required for manual operations would be limited. Productivity of personnel was not measured, but was assumed to be on par with, for example, mining operations. All employment in the category harvesting, compilation and to a limited extent chipping feedstock to size for storage would be created on commercial and communal farmland areas. Fast pyrolysis conversion would take place in urban or semi-urban areas. Table 9-1 and Table 9-2 summarise the personnel requirements for harvesting options and therefore the additional employment opportunities created. These are valid for both Namibia and South Africa.

Table 9-1 Personnel needs - complete manual harvesting and compiling operations, requiring unskilled to skilled labour [adapted from 102], expressed in electrical output equivalent

	1 MW [E]	5 MW [E]	10 MW [E]	20 MW [E]
Complete manual harvest	24	64	256	1024
Complete manual compiling	24	64	256	1024
Complete manual chipping	8	16	49	169
Transport	21	49	256	1521
Overall organisation	2	5	10	20
TOTAL	**79**	**198**	**827**	**3 758**

Table 9-2 Personnel needs – fully mechanised harvesting, compiling operations and feedstock preparation, requiring skilled to highly skilled labour; 1 operator per equipment type [adapted from 102], expressed in electrical output equivalent

	1 MW [E]	5 MW [E]	10 MW [E]	20 MW [E]
Skid steer and rotary saw	3	8	15	30
Skid steer and grapple fork for compiling	3	8	15	30
Tractor for chipping	2	4	7	13
Tractor for road transport	3	7	16	39
Chipper	2	4	7	13
Trailer	3	7	16	39
Overall organisation and management	2	5	10	20
TOTAL	**18**	**43**	**86**	**184**

The need for personnel associated with harvesting operations does not grow with the same rate as electrical output increases. This is mainly because of economies of scale achieved with increased fast pyrolysis plant capacity and therefore increased electrical output capacity.

Personnel needs for administrative duties concerned with supply of feedstock and fast pyrolysis conversion processes equivalent to electricity output required are listed in Table 9-3. For administration and management of these operations, skilled and highly skilled workers are required.

Table 9-3 Personnel needs for administration and management of feedstock supply, fast pyrolysis conversion and sales, expressed in electrical output equivalent

	1 MW [E]	5 MW [E]	10 MW [E]	20 MW [E]
Procurement	0.5	1.5	2	5
Sales	0.5	0.5	2	2
Operations and maintenance (technical)	5	7	37	72
Finance	0.5	1	3	3
Human capital	0.5	1	3	5
Daily administration	1	1	5	5
Overall organisation and management	2	2	4	4
TOTAL	**9**	**14**	**56**	**96**

9.4 NAMIBIAN FAST PYROLYSIS OPERATIONS

9.4.1 Breakeven selling price for feedstock

Feedstock prices were assessed based on an annual harvesting of 500ha per farm and an 80% infestation level of total harvestable bush in the Okakarara and Otjiwarongo farmland districts respectively (Table 9-4). The breakeven selling price includes harvesting and on-farm (10 km) transport costs only; comminution or chipping cost was excluded as this cost was included in fast pyrolysis operations part. The harvesting excludes the already existing uses of bush material elsewhere.

Table 9-4 Breakeven selling price for feedstock and on-farm harvesting personnel requirements to sustain harvesting operations on Namibian farms

Harvesting Method	Okakarara feedstock breakeven selling price (NAD wet-t^{-1})	Mean harvesting personnel requirements per farm	Otjiwarongo feedstock breakeven selling price (NADwet-t^{-1})	Mean harvesting personnel requirements per farm
Manual harvesting for all clearings	30	187	29	248
Fully mechanised harvesting for initial clearing; thereafter semi-mechanised harvesting and manual clearings	36	91	45	120

The number of on-farm employment created (Table 9-4) is based on the amount of personnel required per type of harvesting operations (Table 5-4 and Table 5-20) to clear 500ha off bush annually, on the Okakarara and Otjiwarongo farms respectively. This number is not linked to the electrical output requirements (these were established separately).

The breakeven selling prices for feedstock (Table 9-4) are relatively low. However, for each additional on-farm transport-km to be driven, the feedstock price increases by NAD2/wet-t. The low feedstock price is mainly explained by the benefits that clearing or harvesting have on rangeland rehabilitation and consequently increased livestock production output because more grazing becomes available. The feedstock breakeven selling price decreases proportionately with improved carrying capacity of the farmland.

In addition, harvested bush would still need to be chipped to desired feedstock size, therefore requiring additional handling and transport which attracts additional costs not reflected in the breakeven selling price. Uncertainty induced due to potential on-farm labour unrests (section 4.3.2) poses great risk on sustainability of feedstock supply; therefore potentially jeopardising any benefits the farmer could have for continued income generation, improved carrying capacity, increased livestock production output, and ultimately sustainability of fast pyrolysis operations for bioenergy generation at national level.

9.4.2 Annual feedstock supply

For the Okakarara farmland area, an average of 14.8kwet-t (or 286wet-t/week or 58wet-t/work-day) wood could be produced per farm over a 20 year period. In years 6, 7 and 8 on-farm wood production could be as high as 33.5kwet-t/annum. In the Otjiwarongo farmland area, an average of 19.6kwet-t (or 278 wet-t/week or 68wet-t/work-day) would be produced per farm over a 20 year period. The highest production of 44.3kwet-t/annum is noted for combined Okakarara and Otjiwarongo farmland areas for the years 4 to 8. To assist the farmers to handle such large quantities of wood which need to be harvested and transported on an annual basis, it is necessary to offer logistical support services. Logistical support services include appropriate feedstock storage and regular transport from the farm to the fast pyrolysis conversion site and/or buffer storage site. Farmers could store the feedstock for a limited period of time only before it deteriorates, especially in the summer season when it rains. However, feedstock should be supplied consistently throughout the year to sustain fast pyrolysis operations. Feedstock should thus be collected from several farms at regular intervals on an appointment bases thereby optimising feedstock supply to enhance feasibility and economic viability of fast pyrolysis operations.

9.4.3 Conversion processes and breakeven product selling prices

For the various harvesting methods and resultant feedstock breakeven selling prices the feasibility and economic viability of fast pyrolysis operations were analysed. No manufacturing incentives or potential rebates that could be provided by the Namibian government (e.g. CO_2 rebates through the ‘Clean Development Mechanism’) were taken into account. The breakeven selling price was determined for bioenergy products (bio-oil and electricity-equivalent) at the conversion site and taking into consideration that fast pyrolysis operations could be either equity or loan funded, or a combination thereof. Table 9-5 presents the results for a 100% loan financed pyrolysis operations. The even-valued feedstock price of NAD100/t was taken as proxy (dummy value). It was assumed that the feedstock price would be fixed, and not fluctuating depending on which harvesting method was used to deliver such feedstock to the fast pyrolysis operations.

Table 9-5 Price for bioenergy products via fluidised bed fast pyrolysis, expressed in required electrical output equivalent using a feedstock price of NAD100/t; investment funded on a 100% loan basis; feedstock is derived from bush encroachment in Okakarara and Otjiwarongo farmland area

Required electrical output	Feedstock costs ($NADt^{-1}$) - comparative	Transport distances (km)	Main product	Breakeven selling price
1 MW	100	100	bio-oil electricity	NAD 620/t NAD 0.51/kWh
5MW	100	100	bio-oil electricity	NAD 503/t NAD0.33/kWh
10 MW	100	100	bio-oil electricity	NAD 487/t NAD 0.29/kWh
20 MW	100	100	bio-oil electricity	NAD 488/t NAD 0.29/kWh

Prices of bio-oil increase substantially as feedstock prices and transport distances increase. The sharpest price increase for bio-oil is noted when feedstock prices increase from its breakeven selling price (Table 9-4) respectively to NAD100/wet-t. The bio-oil prices increase with more than 30% when the feedstock price increases from their breakeven selling price to NAD100/wet-t and by some 15% if the feedstock price increases from NAD100/wet-t to NAD200/t; Table 9-6 shows how for each fast pyrolysis process considered. When the transport distance increases from 100 to 200km, the bio-oil breakeven price increases by between 58% for a 1t/h to 74% for a 20t/h fast pyrolysis operation at a feedstock price of NAD100/t. Table 9-6 shows how feedstock price increases together with transport distance increase from 100 to 200km influences bio-oil price under 100% loan funded operations.

Table 9-6 Breakeven selling price for bioenergy products via fluidised bed fast pyrolysis; investment funded on a 100% loan basis; feedstock is derived from bush encroachment in Okakarara and Otjiwarongo farmland areas

Required electrical output	Feedstock costs ($NADt^{-1}$)	Transport distances (km)	Main product	Breakeven selling price
1 MW	100	200	bio-oil	NAD 978/t
			electricity	NAD 0.81/kWh
	200		bio-oil	NAD 1,170/t
			electricity	NAD 0.97/kWh
	300		bio-oil	NAD 1,362/t
			electricity	NAD 1.13/kWh
5MW	100	200	bio-oil	NAD 862/t
			electricity	NAD0.57/kWh
	200		bio-oil	NAD 1,054/t
			electricity	NAD0.70/kWh
	300		bio-oil	NAD 1,245/t
			electricity	NAD 0.82/kWh
10 MW	100	200	bio-oil	NAD 845/t
			electricity	NAD 0.50/kWh
	200		bio-oil	NAD 1,037/t
			electricity	NAD 0.61/kWh
	300		bio-oil	NAD 1,229/t
			electricity	NAD 0.73/kWh
20 MW	100	200	bio-oil	NAD 847/t
			electricity	NAD 0.50/kWh
	200		bio-oil	NAD 1,038/t
			electricity	NAD 0.61/kWh
	300		bio-oil	NAD 1,230/t
			electricity	NAD 0.73/kWh

The breakeven selling price for bio-oil drops considerably between the 1t/h fast pyrolysis option and the 5t/h option; thereafter the breakeven selling price drops further for bio-oil produced in a 10t/h fast pyrolyser, and increases for the 20t/h fast pyrolyser when feedstock costs and transport distances increase. It seems that the economies of scale for fast pyrolysis lie between a 5t/h and 10t/h operational unit.

The price/t bio-oil produced in a 5t/h fluidised bed fast pyrolysis at a feedstock cost of NAD100/wet-t and completely loan funded capital expenditure can be favourably compared with currently used coal-based electricity production. The bio-oil breakeven selling and thus electricity prices are very price sensitive to funding structure changes.; Table 9-7 shows how. As loan funding decreases, prices of bio-oil and thus electricity increase. The reasons lie with taxes that become payable and relatively high discount rate. The sharpest price increases for the type of funding used was noticeable with the 1t/h fast pyrolysis unit of some 65% between 100% loan funded and 100% equity funded operations.

Table 9-7 Breakeven selling price for bioenergy products via fluidised bed fast pyrolysis; investment funded on a 100%, 75% or 0% loan basis; feedstock at a cost of NAD100/wet-t is derived from bush encroachment in Okakarara and Otjiwarongo farmland areas together; feedstock is transported for a maximum of 100km

Required electrical output	Feedstock costs ($NADt^{-1}$)	Type of loan funding (%)	Main product	Breakeven selling price
1 MW	100	100	bio-oil	NAD 620/t
			electricity	NAD 0.51/kWh
		75	bio-oil	NAD 721/t
			electricity	NAD 0.60/kWh
		0	bio-oil	NAD 1026/t
			electricity	NAD 0.85/kWh
5MW	100	100	bio-oil	NAD 503/t
			electricity	NAD 0.33/kWh
		75	bio-oil	NAD 589/t
			electricity	NAD 0.39/kWh
		0	bio-oil	NAD 844/t
			electricity	NAD 0.56/kWh
10 MW	100	100	bio-oil	NAD 487/t
			electricity	NAD 0.29/kWh
		75	bio-oil	NAD 570/t
			electricity	NAD 0.34/kWh
		0	bio-oil	NAD 818/t
			electricity	NAD 0.48/kWh
20 MW	100	100	bio-oil	NAD 488/t
			electricity	NAD 0.29/kWh
		75	bio-oil	NAD 569/t
			electricity	NAD 0.34/kWh
		0	bio-oil	NAD 812/t
			electricity	NAD 0.48/kWh

Bio-oil prices are very sensitive to feedstock prices, transport distance and type of funding mechanisms used for the fast pyrolysis operations. In general, the electricity breakeven selling prices for all pyrolysis options fall within the suggested REFITs as presented in Table 5-26. However, bio-oil prices for all fast pyrolysis options presented are higher than the NAD714.40/t benchmark presented in Table 5-27. Bio-oil prices compare favourably with industrial grade Diesel, though (Table 5-27).

As initially assumed, fast pyrolysis operations smaller than 5t/h come at a higher cost. The 1t/h fast pyrolysis operations are most sensitive to feedstock price, transport distance and selected funding mechanisms.

9.4.4 Land use and other gains

In Namibia, the objective to clear a substantial amount of bush encroachment is based on the need to put infested agricultural land back into productive livestock farming areas. In the case of Okakarara, the rangeland improves its carrying capacity (refer to definition 3.4.6) by some 1.1%

per annum or some 360g live body mass per farm area/annum; for the Otjiwarongo farmland area carrying capacity is improved by 1% per annum or 290g live body mass/annum. This means that after 20 years of consecutive bush harvesting, the rangelands of Okakarara would have improved its carrying capacity from 28.57kg/ha to 45kg/ha; in the Otjiwarongo farmland area, carrying capacity would have improved from 23.04kg/ha to 28.80kg/ha. In both cases, this falls short of the envisaged target of 45kg/ha for the Okakarara; and 42.24k/ha for the Otjiwarongo farmland area respectively. It can therefore be concluded that rangeland rehabilitation needs time, but is beneficial in socio-ecological and economical terms. Table 9-8 summarises the gains from reducing bush encroachment in Namibia.

Table 9-8 Summary of approximate land use and other gains from clearing encroachment bush consecutively, and according to suggested harvesting plans over 20 years at a rate of 500ha per farm

Farmland area	Weighted average bush density (tha^{-1})	Land gain (Mha)	Grass production in treated areas	Carrying Capacity (kg ha^{-1})
Okakarara	2013: 45.55 after 20 years of treatment: 42.08	some 0.5	At least 10-fold, and recovery of perennial grass species	2013: 28.57 after 20 years of treatment: 35.71
Otjiwarongo	2013: 60.19 after 20 years of treatment: 43.60	~1.1	At least 10-fold and recovery of perennial grass species	2013: 23.04 after 20 years of treatment: 28.80

The relatively low breakeven selling price for wood harvested manually (Table 9-4) suggests that the minimum wage of some NAD220/worker/month, is very low. Therefore the assumed (dummy) feedstock price of NAD100/wet-t seems reasonable as it could enable farmers to pay their workers a higher wage and provide the farmer additional income without jeopardising feasibility of fast pyrolysis operations.

9.5 SOUTH AFRICAN PYROLYSIS OPERATIONS

9.5.1 Price for feedstock

As in the Namibian case, the breakeven selling price was determined considering two harvesting options and two bush encroachment densities (section 6.2.3; Table 9-9). Feedstock from alien wood species is assumed to be availed for fast pyrolysis conversion free of charge. However, all feedstock types have to be transported from the harvesting areas to the buffer storage and/or fast pyrolysis conversion site; costs for transport and comminution were taken into account in computing the breakeven selling price of bio-oil.

Table 9-9 Breakeven selling price for feedstock from bush encroachment to sustain harvesting operations on South African farms; average farm size of 300ha

Harvesting Method	Breakeven selling price for feedstock; woodland canopy cover >50% (ZAR/wet-t)
Manual harvesting for initial clearing; follow up and aftercare treatments are also done manually	65
Fully mechanised for initial harvesting; semi-mechanised harvesting for follow up treatments; manual for aftercare treatments	97

The breakeven selling prices for feedstock include on-farm transport of 5km of the harvested wood material. This distance is shorter than in the Namibian case, as farm sizes are smaller. Feedstock prices are sensitive to transport distances. Should there be no on-farm transport, the breakeven feedstock price is lowered with ZAR9/wet-t for the harvesting methods provided in Table 9-9. As in the Namibian case, this means that for each on-farm transport-km of the feedstock, some ZAR2/wet-t needs to be added to the feedstock price, which has a significant influence on the feedstock price. The price sensitivity is explained by the relatively slow rehabilitation process of the rangeland and biodiversity which served as basis for modelling feedstock prices. The influence on feedstock price of farm size and area to be harvested annually is insignificant.

9.5.2 Fast pyrolysis conversion product prices

Under South African circumstances two types of wood based biomass resources were considered to be converted in bio-oil by fluidised bed fast pyrolysis: invasive alien wood-based plants in Eastern and Western Cape and bush encroachment in woodlands, and the fast pyrolysis plant suggested would be located in Gauteng Province.

As per the invasive alien plants eradication programme of the South African government, these plants are cleared by mainly applying of arboricides with manual follow-up and aftercare treatments, or complete manual harvesting and extraction of such plants. Follow-up and aftercare treatments are assumed to start two to three years after the initial treatment. In line with the objectives of this research, it is assumed that complete manual and/or semi-mechanised and mechanised operations are used for initial harvesting operations to clear bush encroachment in woodlands and eradication of alien plants. Transport and comminution of feedstock costs are part of the costing approach. As in the Namibian case, different feedstock prices and types of capital expenditure funding were considered. Table 9-10 summarises the resultant breakeven prices for bio-oil derived from bush encroachment and invasive alien plant species in fluidised bed fast pyrolysers.

Table 9-10 Breakeven selling price for bioenergy products via fluidised bed fast pyrolysis; investment funded on a 100% loan basis; feedstock is derived from bush encroachment and/or alien plant species; transport distances from farms to Gauteng is no longer than 200km

Location of fast pyrolysis plant	Feedstock type	Feedstock price (ZAR wet-t^{-1})	Breakeven bioenergy selling price in equivalent of desired electrical output (ZAR t^{-1} or ZAR kWh^{-1})	
			1 MW	**5 MW**
Gauteng	Wood from bush encroachment	100	Bio-oil: 978 Electricity: 0.81	Bio-oil: 829 Electricity: 0.55
Eastern Cape	Wood from invasive alien plants	0	Bio-oil: 686 Electricity: 0.57	
Western Cape	Wood from invasive alien plants	0	Bio-oil: 761 Electricity: 0.63	Bio-oil: 649 Electricity: 0.43

Although wood-based feedstock is available in abundance in South Africa, the residual amounts are not sufficient to realise sustainable fast pyrolysis operations beyond the required electrical output of 5MW. This is due to two main reasons: the relatively low bush encroachment density in South Africa requires a larger area from which wood would need to be harvested than in Namibia; and considering that alien plant species are eradicated within the 'Working for Water' project parameters from which only a limited amount of wood would be available for fast pyrolysis conversion annually.

The breakeven selling prices for bioenergy products change significantly with feedstock price changes. Should the 'Working for Water' e.g. charge a fee of ZAR100/wet-t for wood from alien plant species, the price for bio-oil produced in the Eastern Cape would change from ZAR686/t to ZAR 859/t; and the electricity breakeven price from ZAR0.57/kWh to ZAR 0.71/kWh. Table 9-11 summarises the effect of feedstock price on bioenergy products.

Table 9-11 Breakeven selling price for bioenergy products via fluidised bed fast pyrolysis subject to varying feedstock prices; investment funded on a 100% loan basis; feedstock is derived from bush encroachment and/or alien plant species in different locations; transport distances of 200km

Location of fast pyrolysis plant	Feedstock type	Feedstock price (ZAR wet-t^{-1})	Breakeven bioenergy selling price in equivalent of desired electrical output (ZAR t^{-1} or ZAR kWh^{-1}) 1 MW	5 MW
Gauteng	Wood from bush encroachment	100	Bio-oil: 978 Electricity: 0.81	
		200	Bio-oil: 1,170 Electricity: 0.97	
		300	Bio-oil: 1,362 Electricity: 1.13	
Eastern Cape	Wood from invasive alien plants	100	Bio-oil: 859 Electricity: 0.71	
		200	Bio-oil: 1,032 Electricity: 0.85	
		300	Bio-oil: 1,205 Electricity: 1.00	
Western Cape	Wood from invasive alien plants	100	Bio-oil: 949 Electricity: 0.79	Bio-oil: 837 Electricity: 0.55
		200	Bio-oil: 1,137 Electricity: 0.94	Bio-oil: 1,025 Electricity: 0.68
		300	Bio-oil: 1,326 Electricity: 1.10	Bio-oil: 1,213 Electricity: 0.80

As in the Namibian case, the effect of amount of loan funding required for the investment is relatively small if compared to the effect that transport or feedstock costs have on bioenergy breakeven selling prices. For all South African pyrolysis options considered, the breakeven electricity selling price drops by not more than 3ZAR-cents between a 100% loan funded versus a 100% equity funded operation. However, breakeven electricity prices are within the proposed national REFITs for biomass based electricity production (Table 5-28).

9.5.3 Land use and other gains

If a 5t/h fast pyrolyser is considered to convert South African wood from bush encroachment to bioenergy, some 5.47Mha, at an average wood yield of 10.8wet-t/ha, of land needs to be cleared annually. This means that after 20-years some 16Mha of land would have been cleared at least once. It therefore is not economically viable to engage in setting up a fast pyrolysis plant with a capacity of more than 5t/h. Table 9-12 summarises the land use gains.

Table 9-12 Summary of approximate land use gains from clearing encroachment bush or alien plant species consecutively, and according to suggested harvesting plans in South Africa over 20 years

Type of area affected by problem plant species	Weighted average plant density (tha^{-1})	Land use gain (Mha)	Annual average area to be cleared (ha)
Bush encroachment in woodlands area	2013: 11.67 after 20 years of treatment: 10.87	5.47	810,000
Alien plant species in the Eastern Cape	2013: 69.7 after 20 years of treatment: ~6.4	~0.18	17,950
Alien plant species in the Eastern Cape	2013: 111 after 20 years of treatment: ~10.2	~0.42	37,401

9.6 BIO-OIL PRICE COMPARISON

Bio-oil prices as computed in this research for Namibia and South Africa compare well with those in Europe and the USA for example. The price comparisons are presented in Table 9-13.

Table 9-13 Bio-oil breakeven selling price comparisons

Country or region	Breakeven selling price range ex production site (NAD or ZAR t^{-1})	Breakeven selling price range ex production site (NAD or ZAR/GJ)
Namibia	620 – 1245	26 to >70
South Africa	859 – 1326	45 to 75
Europe	982.85 – 1,601.34 [330]	64.20 – 104.60 [330]
USA	8,137 - 19,867 [331]	215.10 [332]

9.7 MACRO-ECONOMIC BENEFITS

A number of macro-economic gains could be derived by harvesting unwanted wood-based biomass resources for bioenergy production. These include:

- Additional total employment creation, of between 800 to 1,000 for both harvesting and fast pyrolysis operations, for the desired, respective electrical output.
- Additional taxation, depending on the funding and harvesting model as well as the desired electrical output, amounts of between NAD110 billion (1MW equivalent) to NAD 1,567 billion (20MW equivalent) could be collected by the Namibian State over a 20-year period. In South Africa, this benefit could amount to ZAR224 billion for a 1MW equivalent, and some ZAR5,645 billion for a 5MW equivalent output operation.
- For each MW of electricity supplied, an additional 2,000 households could be supplied with electricity each year.

- Gross Domestic Product (GDP) growth, in
  - the primary agriculture sector,
  - the financing sector, mainly in the form of capital formation
  - the energy sector.

By considering only the additional amount of taxes collected each year the Namibian economy could additionally grow by 0.2% annually. If the contribution to agriculture, the financing and the energy sector are added, this contribution could grow by some 0.5% annually. In South Africa a similar trend would be possible. However, the South African economy is much larger than the Namibian, and the total additional GDP growth would be expected to grow by some 0.18% annually.

9.8 TECHNICAL AND NON-TECHNICAL BARRIERS TO FAST PYROLYSIS

Based on the lessons learned and experiences of mainly slow pyrolysis in Namibia and South Africa since the 1970s, techno-economic models for fast pyrolysis were built; considering Namibian and South African data in relation to wood-based resource availability and the skills required to sustain fast pyrolysis operations in these countries. Assessing technological viability based on resource availability helped to already exclude certain biomass options for fast pyrolysis before complete economic and/or plausibility assessments are carried out.

9.8.1 The Namibian case

Even though feedstock supply contracts would be expected to be concluded between operators of the fast pyrolysis system, incentives would be needed to on a large scale harvest the wood from bush encroachment areas to secure a feedstock supply chain for bioenergy production systems. The financially based incentives and governance support systems that would be required include:

- guarantees for independent power supply into the national grid;
- secured feed-in tariffs for electricity supplied into the national grid;
- offer CO_2-emissions mitigation rebates and allowance for a CO_2 trading platform;
- relaxation of or concessions to be made under immigration laws to allow for import and dissemination of skills which are not available in Namibia, if/when needed;
- provision of funding for industrial research and development to adopt and adapt new technologies and prototype/commercialise new products; and

- in terms of public-private partnerships (PPPs), offer to take an equity stake in strategic projects like fast pyrolysis for bioenergy.

9.8.2 The South African case

For techno-economic viability of bioenergy production systems like fast pyrolysis to become a reality a number of technical and non-technical barriers need to be overcome:

- because South Africa possesses vast fossil solid and liquid fuel resources there seems to be little appetite for new technology adoption based on biomass resources for national energy production;
- political willingness and rigorous support through mandatory supply and uptake of bioenergy (Table 5-28) on belated implementation of "biomass and biogas"-based electricity feed-in tariffs for independent power production in the national interest);
- relaxation of some of the stringent provisions under environmental laws to open up the market for technological innovations; and
- increasing the availability and access to affordable funding (section 5.4.1, 5.6.2) for bioenergy solutions.

9.8.3 Summary of technical and non-technical barriers

Table 9-14 provides an overview of the most pertinent barriers to be overcome before realisation of macro-economic targets. Technical and non-technical barriers inhibit the ease of application of fast pyrolysis operations in Namibia and South Africa. The information presented herewith is indicative and is guided by the conceptual framework (Chapter 2) and the standards in place to adopt new renewable energy technologies (section 5.5 and 5.6). South Africa was used as a benchmark as laid out in the country's *Energy Plans* [30, 40, 41, 241, 244, 245, 246, 247] and *the Biofuels Industry Strategy* [7]. For the Namibian situation, the targets and standards mentioned in Table 9-14 with regards to renewable energy in general, and bioenergy in particular require confirmation from authorities.

Table 9-14 Technical and non-technical barriers which impede techno-economic viability of new pyrolysis systems to be introduced in South Africa measured against existing initiatives to deploy renewable energy technologies

	Overall aspired outcome (Biomass conversion technologies)	Current & possible additional contribution by use of fast pyrolysis	Techno-economic assessment of past and current situation	
			Non-Technical Barriers	Technical Barriers
Macroeconomic Drivers (policy and planning)	• 26 MW by 2018 in addition to existing renewable supplies • 2% penetration level of final biofuels product, or 400Ml p.a. • no increase in greenhouse gas emissions • development of rural areas • >20k new, sustainable jobs to be created • import substitution of foreign energy sources • trade distortion is overcome	• >60,000 kWh/a from the wood-based biomass resources identified in this research • national food security remains intact • no additional land degradation as no deforestation would take place	• complicated, contradicting legal & regulatory framework for licensing and registration of renewable energy projects which aspire production of alternative energy, even for relatively small generation capacities • limited, and not attractive fiscal incentives, even for additional job creation	• economies of scale achieved by fossil energy based conversion technologies are comparable but not better than those based on fast pyrolysis conversion technologies • fast pyrolysis is a new technology and not commercially proven in Africa yet • the scalability of fast pyrolysis technology beyond 10t/h feedstock intake plants remains a challenge • reliability of fast pyrolysis technology smaller than 2t/h remains a challenge
Microeconomic Drivers (supply side)	• self-sufficient income generation • quick return on investment • profitability • scalability of technology • acceptable quality of product • higher process efficiency	• economic viability with additional job creation is assumed to be achieved • further product quality improvement • expansion of operations • process efficiency	• no or difficult access to limited funding • high labour turn-over • limited skills, and high skills mobility • limited human capacity development • access to feedstock is insecure due to limited land access rights • current operators of conversion technologies already established may compete for similar feedstock • price of feedstock or the fluctuation thereof strongly influences the product price	• lack of choice of commercially available technologies • lack of technological innovativeness • insufficient/ uncertain supply of energy precursors (e.g. biomass) • severe competition for same source raw materials and un-diversified sourcing of feedstock

	Overall aspired outcome (Biomass conversion technologies)	Current & possible additional contribution by use of fast pyrolysis	Techno-economic assessment of past and current situation	
			Non-Technical Barriers	**Technical Barriers**
Market Drivers (demand side)	• acceptable product prices • market preservation, and new market penetration • high quality of product • recognition of new product range • approved labelling • meeting of market standards (e.g. FSC, ISO 9000)	• product diversification subject to quantities • retail markets are lucrative, based on some niche products and ability to certify products (product diversification subject to quantities)	• no mandatory uptake of products (even REFITs are not mandatory) • un-diversified markets impede uptake of new energy products • lack of market knowledge • insufficient quantities of product available which warrants uptake of alternative energy carriers other than current markets available • price developments for energy products are static or regressive	• lack of commitment for technological adjustments to current electricity or heat generating equipment could hamper uptake of bio-oil • limited secondary processing possible or available, i.e. bio-oil refineries • non accommodative market entry standards & certification procedures for new bioenergy products entering the market

9.9 CONCLUSIONS

Fluidised fast pyrolysis of feedstock from Namibian and South African encroachment bush and alien plant species in the Eastern and Western Cape, South Africa is feasible. The breakeven selling prices of bio-oil and electricity produced in Namibia and South Africa compare favourably with in-country prices, as well as with those of Europe and the United States of America. The breakeven bio-oil selling price is very sensitive to feedstock and transportation costs as well as feedstock characteristics; but less sensitive to capital expenditure funding types, i.e. loan or equity funding.

Power production via fast pyrolysis is an attractive technology as the final product prices fall within current price levels of electricity prevalent in Namibia and South Africa respectively. However, economic viability and bankability of bioenergy production based on wood-based fast pyrolysis could not be conclusively proven. Fast pyrolysis is a new technology, even in Europe and North America, where fully commercialised operations are still under implementation.

Fast pyrolysis is CO_2-emissions neutral, and could thus be an alternative to current methods of electricity production systems used in Namibia and South Africa. Nevertheless, the policy setting seems to suggest that the deployment of such new technology is neither economically viable nor bankable. Furthermore, fiscal incentives would be the only enabler offered by these states to overcome this hurdle. However, the administrative system to obtain them seems to be overly challenging.

In conclusion, while fast pyrolysis is feasible in both Namibia and South Africa, the political and economic settings do not readily embrace this novel approach to power production, and/or addressing bush encroachment in Namibia and South Africa, and invasion of alien plant species in South Africa. Unless macro-economic and nationally embraced strategic interventions take place, the bankability of fast pyrolysis for bioenergy production is expected to remain a challenge. The future interventions required to make fast pyrolysis an economically viable option were outlined in Chapter 10.

10 CONCLUSIONS AND RECOMMENDATIONS

The primary objectives of this research were to:

- Collect, analyse and model biomass resource data in Namibia and South Africa;
- Analyse, evaluate and provide recommendations on the current and predicted Namibian and South African fast pyrolysis industry;
- Analyse and evaluate opportunities for the use of fast pyrolysis to convert the wood-based biomass into bioenergy in Namibia and South Africa;
- Assess the environmental and techno-economic sustainability of fast pyrolysis systems to produce bioenergy (e.g. power, heat or fuel) from wood-based biomass resources in Namibia and South Africa.

To fulfil the primary objectives, the scope of work in more detail related to:

- modelling wood-based biomass resources;
- assessing the possibilities and challenges to introduce fast pyrolysis for bioenergy production;
- producing a techno-economic model, including future prediction, opportunities and constraints for bioenergy production via fast pyrolysis;
- assessing the feasibility and techno-economic viability of fast pyrolysis;
- defining the resources and skills required to operate a fast pyrolysis process; and
- if bioenergy production via fast pyrolysis was found to be feasible and economically viable, producing a "roadmap" for technology deployment and a timescale to achieve market penetration for products derived from fast pyrolysis, including the need for knowledge and technology transfer.

Furthermore, the question was posed whether a benchmark could be established to use bush for bioenergy in a sustainable manner in the Namibia case, and if so what would be the parameters needed to constitute such benchmark. Is the Namibian socio-economic and techno-economic environment 'right' to embrace a modern bioenergy system?

10.1 CONCLUSIONS

There are uncertainties related to the use of fast pyrolysis for electricity production in both Namibia and South Africa. However, there are considerable opportunities to exploit excess encroacher bush in Namibia, and both encroacher bush and alien invasive plant species in South Africa for improved land management, generation of biomass resources, and establishment of new technology in Southern Africa. With the generation of biomass resources and subsequent thermo-chemical conversion of the biomass, new job opportunities could be created, know-how and technology transfer could take place, which both could lead to GDP growth over the medium to longer term.

10.1.1 The Namibian case

The Namibian wood-based biomass resources, in the form of bush encroachment, are spread over an area of 30 Mha. Following an analysis of potential yield, the study area was limited to sourcing of feedstock for fast pyrolysis operations to the Okakarara and Otjiwarongo farmland areas comprising an area of 5Mha, where high-density bush encroachment exists. Fast pyrolysis operations were considered to be located close to or in Otjiwarongo-town, which is located centrally to the Okakarara and Otjiwarongo farmland areas and closely located to the power transmission hub 'Gerus'. This warranted the consideration for modelling various fast pyrolysis operations that would not impede existing slow pyrolysis and firewood production systems or domestic use of wood for energy. The four proposed fast pyrolysis operations, i.e. 1, 5, 10 and 20t/h fast pyrolyser options for electricity, heat and/or fuel production, were analysed to be feasible; proving its economic viability would pose a challenge.

It seems that multiple fast pyrolysis operations of varying capacity could be sustained across Namibia; this would be based on extrapolating the results of fast pyrolysis operations analysis from the Okakarara and Otjiwarongo areas, i.e. some 5Mha, to bush encroached areas of 30Mha on a national basis. However, a national, strategic initiative should include planned investments for the installation of the new fast pyrolysis systems for electricity generation. This could include the upgrading of existing slow pyrolysis systems to more efficient and effective slow pyrolysis operations. Feasibility considerations then need to include additional cost factors for skills development, technology transfer and pro-active marketing of fast pyrolysis products.

In principle it was found that the socio-economic setting of Namibia is receptive to the introduction of new technology, such as fast pyrolysis for bioenergy production. Wood from bush encroachment is a feasible feedstock resource for fast pyrolysis conversion. Deliberate national interventions or strategies would be required to embrace new energy generation technologies in general. In addition, there are challenges that impede the establishment of a benchmark. These relate to the implementation of knowledge and technology transfer as well as feedstock supply side and product market constraints. Knowledge and technology transfer is limited by the non-availability of the required number of skilled personnel in the field of bioenergy and quantitative data on biomass and bioenergy markets. Technological adaptability is the major factor that inhibits technology transfer. Possible and existing feedstock supply side constraints allude to:

- accessibility to the wood resource;
- limitations to the current harvesting techniques and introduction of large-scale mechanised harvesting;
- high harvesting and transportation costs of the feedstock; and
- limitations of farmers to supply feedstock on a regular basis as agricultural production is their first priority, and do not necessarily concern wood harvesting and supply unless incentivised in some manner.

10.1.2 The South African case

The encumbering factor to prove techno-economic viability of fast pyrolysis systems in South Africa is availability of sufficient wood-based resources over the long term. As mentioned in section 4.1.3.2, residues suitable for fast pyrolysis from commercial forestry activities are not viable; and, wood-based biomass resources from bush encroachment and alien plant species are also limited (section 9.5). It may be a consideration to further enhance currently used slow pyrolysis technology to increase resource efficiency operations as existing markets for charcoal prevail. For example, harvesting exhaust gases to pre-dry feedstock may reduce the biomass resource and pyrolysis retention time requirements per kiln or retort slow pyrolysis cycle considerably; thereby enhancing profitability of each operation. Short term investments would need to be made, but over the long term, product quality and acceptability benefits, e.g. sustainability standards like the Forest Stewardship Council (FSC) that need to be adhered to, would certainly outweigh the costs.

Biomass resources from bush encroachment and invasive alien plant species are not sufficient to sustain the development of fast pyrolysis operations beyond the 5t/h scale. As clearing of invasive alien plants in the Eastern and Western Cape provinces enjoy national priority and harvesting operations are largely subsidised, economic viability of fast pyrolysis operations is supported. Such fast pyrolysis operation would not compete with existing slow pyrolysis and firewood production systems nor supply of wood for domestic energy use in the Eastern and Western Cape Province respectively. Finding the optimal location is a limiting factor. A 5MW electricity output equivalent fast pyrolysis operation is only viable in the Western Cape.

Of all South African provinces, Cape Town (the provincial capital of Western Cape) is the only authority that incentivises power production sovereign from the national grid by sourcing power from independent power producers, mainly based on renewable energy sources; a unique situation in the South African power generation landscape. Additional feedstock to sustain a fast pyrolysis operation beyond the supply of feedstock from the Working for Water programme may also be sourced from domestic waste collected by municipal services. This aspect was not covered in this research and would need further analysis. However, after the invasive alien plant species would be eradicated, the feedstock for the fast pyrolysis operation would necessarily need to be switched from wood-based biomass feedstock to an alternative. This research therefore suggests that a fast pyrolysis operation based on feedstock from invasive alien plant species be located in the Western Cape, and optimally in the metropolitan area of Cape Town.

Only one fast pyrolysis plant based on feedstock supply from bush encroachment in the Limpopo, Mpumulanga and/or Northwest provinces in South Africa is feasible. However, proving economic viability needs to be based on additional factors which were not included in the considerations of this research. This research suggested the optimal location to be in the Gauteng Province due to the high density of energy infrastructure there. However, bush densities and specific wood yields of all provinces have not been investigated. It may therefore be that a more feasible location could be found in the other provinces, which would then affect the economic viability further.

10.1.3 Wood-based biomass resources

Namibia has one type of biomass resource available in abundance, wood from bush encroachment. Over a 20-year period, bush encroachment should decrease to restore agricultural production land. The wood-based biomass available is in excess of 25Mwet-t per annum. Both harvesting and various fast pyrolysis conversion options are feasible. However, capacity to harvest and supply large amounts of wood on an annual basis is questionable under existing socio-economic conditions in Namibia. The reasons are manifold and include:

- Mechanisation of harvesting of the wood-based biomass is limited: the type of wood biomass resource, i.e. bushes, limits the degree of mechanised harvesting; a limited skills base exists under the labour force which is typically employed in the agricultural and forestry industry; and the geographic layout of Namibia does not always allow for access to the bush-encroached land for heavy machinery.

- The biomass resource is dispersed over an area of 30Mha and yields vary greatly.
- Logistical, transport, comminution and handling costs associated with the biomass supply to fast pyrolysis operations are high.
- The biomass resource is privately owned by farmers and/or rural communities governed by traditional leaders. Access to the resource is not free and must be arranged on a contractual basis.

In the South African context, two types of wood-based biomass resources were analysed, to be derived from bush encroachment and invasive alien plant species. The collective potential biomass resource base is vast, totalling over 20Mwet-t/year, but highly dispersed over the country. Apart from encroacher-bush, the biomass resources are readily available and no additional harvesting is required. Considering fast pyrolysis conversion of these resources over the long term, the following challenges could be encountered:

- Biomass resources are dispersed over the country, and where the resources occur, the concentration is not high enough to warrant fast pyrolysis operations beyond a feedstock intake of 5t/h.
- Bush encroachment in South Africa occurs over more than 19Mha, posing harvesting and logistical challenges to concentrate the feedstock intake for large fast pyrolysis conversion processes to one central point. The cost of logistics drives the price of the feedstock.

10.1.4 Pyrolysis industry

In both cases, Namibia and South Africa, there is a certain amount of resistance to accept new technologies in general even more so where a similar kind of technology has been used for decades, but the technology has not been technologically improved or adapted to account for technological advancement, for example slow (kiln) pyrolysis processes. Also, coal-based energy is still cheap and based on combustion technology to convert the coal to electricity which is commercially proven and reliable. Industry regulations are less important in deciding on a ‘new’ technology option, however environmental regulations to introduce renewable energy production technology are rather stringent. Legislation classifies pyrolysis, i.e. mainly charcoal manufacturing as a scheduled industry, subjecting it to all industrial norms and specifications relevant when start-up or expansion of any industrial activity is planned. These regulations have to be adhered to, also by small scale slow pyrolysis operations like kilns. Introducing improved pyrolysis or the new fast technology would require a number of steps to be followed and robust reason why and how a new technology would be more effective and profitable than the existing one. A "roadmap" would be required to explain what and how new technologies can be introduced in the market.

Fast pyrolysis processes provide additional economic viability and feasibility over slow pyrolysis retort processes. However, the technical and non-technical barriers to be overcome impede a 'simple' switch over or up-scaling from kiln to fast pyrolysis systems. People's mind-set seem to be fixed on relatively small scale slow (kiln) pyrolysis operations. However, fast pyrolysis operations are large scale which poses a huge challenge in terms of management capacity and capital investment. Therefore, perceived technical and non-technical barriers have to be overcome before investment in the advanced fast pyrolysis technology would be made. Consequently, the better the parameters are defined and explained, the easier it would be to introduce the advanced fast pyrolysis technology in Namibia and South Africa.

10.1.5 Costs of and markets for bio-oil

From the analyses, bio-oil can be produced in a cost efficient manner. The breakeven selling price for bio-oil produced in Namibia is from NAD620/t and depending on the feedstock intake capacity and price. In South Africa, the breakeven selling price of bio-oil is from some ZAR850/t. These prices compare well with the price of ZAR714/t for South African coal exported to Namibia for electricity generation. The average price of coal produced and used in South Africa for energy production in general is below ZAR400/t. Thus bio-oil prices cannot compete with the prices of coal, posing a challenge for bio-oil to enter the South African energy market, unless incentivised by government policies, in this case for example guaranteed renewable energy feed-in tariffs (REFITs).

Bio-oil can ideally be used to produce heat, power or fuels. However, because the biomass resources in Namibia and South Africa are dispersed, not enough quantities can be produced at any production site to warrant more than the production of one product category, for example power.

Bio-oil can ideally be used to produce off-grid electricity in specific communities located close to the biomass resource. On-grid electricity production is a possibility. Although the enabling environment in Namibia and South Africa exists for feeding electricity into the national grid, implementation thereof is cumbersome. Only the metropolitan city of Cape Town, South Africa offers independent power producers the possibility to feed electricity into the municipal power supply grid.

10.1.6 Other challenges that could hamper the introduction of fast pyrolysis technology

The challenges encountered with retort systems and reasons why kilns are still the preferred technology for thermo-chemical conversion of wood-based biomass in Namibia and South Africa are (not mentioned in order of priority):

- There are no markets for the co-products generated by the slow pyrolysis retort, thus assumed that these would not be existing for fast pyrolysis processes either.
- It is easier and cheaper to discard an obsolete slow pyrolysis kiln after 10 years of operation and purchase a new one than maintain a sophisticated system, even if such system could have a lifespan in excess of 20 years. Therefore, investment for the introduction of fast pyrolysis equipment could be perceived as overly expensive, and possibly rejected to be adopted as an alternative to slow pyrolysis operations, even if proven to be feasible and economically viable.
- Slow pyrolysis kilns are more 'user friendly', thus even unskilled and semi-skilled workers can operate them. Fast pyrolysis operations management requires a skilled labour force which is not readily available.
- Apart from skilled labour shortages, technological readiness of the labour force is a limiting factor to introducing a new technology. Policy and regulatory impediments aggravate the situation further.
- Potential plant operators and technicians are not sufficiently trained. Skills development is needed to efficiently run fast pyrolysis operations. Training and staff development needs to be conducted; which could significantly increase productivity, enhance adherence to health and safety regulations at the work place and effect further improvement of process controls and sustainability of resource material supply. Intensive training and staff development is limited currently due to their high operational and overhead costs.
- Staff turnover remains very high, due to better salaries and wages being paid in service or mining related industries; and the consequences of the HIV and AIDS pandemic. The latter fact, for example, impedes effective and efficient trainings and skills development as part of staff development and on-the-job training initiatives at private sector level. It is furthermore extremely costly for the private sector to continuously train staff just to maintain capital cost intensive manufacturing systems when kiln systems suffice. The overall production costs based on slow pyrolysis kiln operations were said to be cheaper even if higher input costs (mainly feedstock) would have to be considered.
- There is no real need to switch to 'high-tech' equipment when labour costs are still relatively

cheap, measured against the hourly minimum wage bill. This aspect becomes very questionable when the former two points need to be taken into consideration as well.

- There is a continuing lack of scientific knowledge about resources and new technologies that could be deployed. For example, data is lacking on the appropriate yield that can be harvested from bush encroachment without damaging natural vegetation levels.
- Coupled with the former aspect, the transfer and popularisation of new technology suited for various production levels remains a barrier. Even though much of South Africa's research and development efforts have been directed towards the needs of the established large companies in the past, larger companies in e.g. the charcoal industry have not sustained their operations with more efficient technologies but reverted back to older technologies. New environmental obligations mean technological improvements have to be made to encompass sustainable large and small-scale production systems based on efficient and effective conversion methods. It seems however, that there is little appetite for South African companies to adapt if legislation is not in place which would make technological improvements mandatory, coupled with penalties if not implemented.
- Even though fast pyrolysis systems are feasible, costs on capital expenditure to introduce fast pyrolysis systems are high when compared to the situation in Europe for example. Although, borrowing of capital has become more affordable since 2000 (the national reserve bank reposition rate – 'repo rate' remained stable at around 6% since 2008 if compared to the average 1998 repo rate of 18.5%). Capital formation and access to affordable capital still hampers the fast-tracking of various developmental and technical adjustment costs. Also, key elements of the fast pyrolysis systems need to be imported from Europe and North America. With exchange rate fluctuations the costs of imports tend to be very high, limiting economic viability even further.
- Manufacturing of charcoal by-and-large is still considered to be a cottage industry, or only providing an auxiliary income to other agricultural and forestry activities. This is especially the case in Namibia where the mainstay of agricultural income is generated by rearing livestock.
- There is no contracted or guaranteed linkage between wood-based resource management and primary use of forest products. This would result in a very inconsistent supply of raw materials to fast pyrolysis plants making it difficult for fast pyrolysis operation owners who could produce large amounts of charcoal or new products like bio-oil to sustain their operations; especially when pyrolysis system operators do not own the wood-based biomass resources like forest plantations or bush on farms.

Because of the deep economic integration of Namibia and South Africa the aforementioned challenges are valid for both Namibia and South Africa. Namibia, and in particular South Africa has introduced a number of policies to overcome the challenges, but the introduction of new technologies remains partial. Additional support measures in South Africa are offered to overcome technical and non-technical barriers when introducing advanced technologies in the renewable energy sector. However, the implementation thereof is slow. Support measures in Namibia are very limited. Additionally, administrative red tape hinders the desire to switch to improved, advanced or adapted technologies.

10.2 RECOMMENDATIONS

In an attempt to explain how fast pyrolysis operations could be made viable, the recommendations take the form of a proposed roadmap on what would be need implementation and how to deploy fast pyrolysis technology in Namibia and/or South Africa. The challenges for companies are big and need the assistance from governments and/or regulators. Collaborative efforts are important in launching fast pyrolysis, especially as the technology is advanced, but not yet available on a commercial basis. Table 10-1 provides a summary of the issues to be addressed, based on the conclusions. Unless a conducive macro-economic environment would be implemented and measures to promote new technologies would be taken, a technology deployment roadmap may not be helpful.

Table 10-1 Challenges and opportunities for the introduction and deployment of fast pyrolysis in Namibia and/or South Africa

	Challenges	Opportunities	Who or what can help	When
Policy framework	Conducive policies if they exist, are not implemented (e.g. biofuels directive, renewable energy in general)	Energy market diversification Competition among energy suppliers Reduced price per unit energy	Government should implement existing policies	Immediately
Commercialise fast pyrolysis technology	Fast pyrolysis of biomass at commercial scale requires optimisation before commercial production can begin	Scalable operations that can take up large quantities of biomass Improved economies of scale	Research institutions, e.g. in UK, USA, SA	Short to medium term
Prototype or pilot fast pyrolysis plant	Such is not available or built locally	Import of a demonstration plant for proof of principle Market introduction	Research institutions Private sector	short term
Skills and knowledge network	Skills and knowledge base too small in Namibia / South Africa	Easing the implementation of new technology in the market Import of skills, if/when required Systemic & Operational efficiency	Research institutions (mostly foreign) Tertiary education organisations (local)	immediately

	Challenges	Opportunities	Who or what can help	When
		High productivity Increased success rate on technology deployment Capacity to innovate/ adapt technology to local circumstance Technology/ know how transfer		
Fast pyrolysis champions	They do not exist locally	Role models that can share knowledge Build international connections and networks	Private sector currently operating other pyrolysis systems (ideally) Use universities as agents for change and network with international communities already engaged in fast pyrolysis	Short to medium term
Coordination, ownership and commitment	Much was tried, but often on a one-off basis leading to negative press	Network of like-minded people International partnership Building of market intelligence	Association of like-minded fast pyrolysis champions	Medium term, in parallel with prototyping or commercialisation of technology, and fast pyrolysis champions
Feedstock harvesting, logistics and processing	Several suppliers for feedstock not working together Harvesting limitations due to type of plants delivering wood High costs associated with feedstock preparation	Founding of a cooperative or industry association which serves suppliers by offering feedstock harvesting and logistics services thereby being cost competitive Process integrations to maximise energy efficiency	Newly formed biomass supply cooperative/ association; Working for Water programme coordinators Equipment suppliers	Medium term, once site specific feasibility and economic viability studies are completed
Technical standards, testing,	As no commercialised technologies exists, this is also hard to	Market ready, competitively priced product	Standards authorities Universities, also	Medium to longer term

	Challenges	Opportunities	Who or what can help	When
certification	attain		via international research institutions	
Finance & costs	Cost of introducing new technologies is high		Development financing institutions Governments	Medium to longer term

10.2.1 Technology deployment roadmap process

This section outlines the steps and key questions that a national approach to a fast pyrolysis technology deployment should consider in designing a roadmap process that would lead to the development and uptake of fast pyrolysis technology. There are six vital aspects to consider when designing a 'roadmap' process for fast pyrolysis technology deployment:

- Stakeholder participation
- Resource constraints
- Critical inputs
- Roadmap design
- Buy-in and dissemination; and
- Monitoring, tracking and evaluation.

Table 10-2 provides an overview of what would be required to establish the roadmap process for fast pyrolysis technology development and deployment in Namibia and/or South Africa. In the Namibian case, a non-governmental agency specifically set-up under the auspices of the National Planning Commission (a department under the Office of the President, which is tasked with macro- and socio-economic planning and implementation) could be the most suitable agency to spearhead the process. In the South African situation, the Department of Energy is an appropriate agency to spearhead the roadmap process.

Table 10-2 Roadmap process for deployment of fast pyrolysis in Namibia and/or South Africa

Aspect	Description of what needs to be done
Stakeholder participation	• Identification of key stakeholders in the industry • Assigning responsibilities to certain stakeholders • Identifying which human resources are available to accomplish roadmap activities & priorities in country, and which may need to be secured from elsewhere • Identifying stakeholders critical to roadmap success
Resource constraints	• Identifying skills and tools required to prepare the roadmap • Sourcing funding for the development of the roadmap • Timing of (broad) stakeholder engagement • Availing personnel to manage & implement roadmap development process
Critical inputs	• Analysing appropriate data to establish baseline conditions, set goals and prepare forecasts • Availing essential analytical capabilities & tools for evaluation • Evaluating technology performance & limitations • Providing insight on factors affecting technology adoption • Identifying markets for technology deployment & products • Analysing competitor & market leaders • Identifying private entities critical to technology success • Proposing & costing of pilot or commercial projects • Establishing supply-side constraints • Establishing solutions for harvesting & logistical constraints • Establishing market and marketing channels • Establishing risks & success factors
Roadmap design	• Setting goals & milestones • Providing essential information • Planning for detail required for effective implementation & action • Acquiring supporting data • Assigning activities to organisations for action
Buy-in and dissemination	• Communicating to convey key messages & engage critical partners • Establishing the methods of communication and mechanisms to reach stakeholders & partners • Reinforcing the value of the roadmap and creating buy-in
Monitoring, tracking and evaluation	• Assigning responsibilities for tracking progress towards roadmap goals & milestones • Identifying data & analysis tools to create & track roadmap metrics • Adjusting technology scenarios as time advances • Re-evaluating & updating technology pathways at regular intervals • Adjusting national policies if roadmap targets are not met

10.2.2 Fast pyrolysis deployment roadmap

Considering the information contained in Table 10-1 and Table 10-2, a roadmap for key actions and respective leading roles to achieve milestones for fast pyrolysis technology development and deployment was put together as shown in Figure 10-1. The roadmap is guided by the conclusions as presented throughout this research and key recommendations. The roadmap process is linked to a 10-year project cycle. Thus only key issues to be considered are mentioned in the roadmap. A comprehensive roadmap for fast pyrolysis technology development and deployment in Namibia and South Africa would probably span over a period of 20 to 30 years, i.e. beyond the Vision 2030 (Namibia) and the AsgiSa 2025 (South Africa) period respectively. However, key issues need to be addressed rather soon, else deployment of fast pyrolysis technology would be absorbed into greater socio-economic development issues or overall renewable energy technology deployment. Thereby, other considerations of why fast pyrolysis is offered to be a solution to successfully eradicate alien plant species or use wood from bush encroachment for agricultural development; create sustainable employment; and diversify biomass value addition options while providing additional energy capacities would be forgotten.

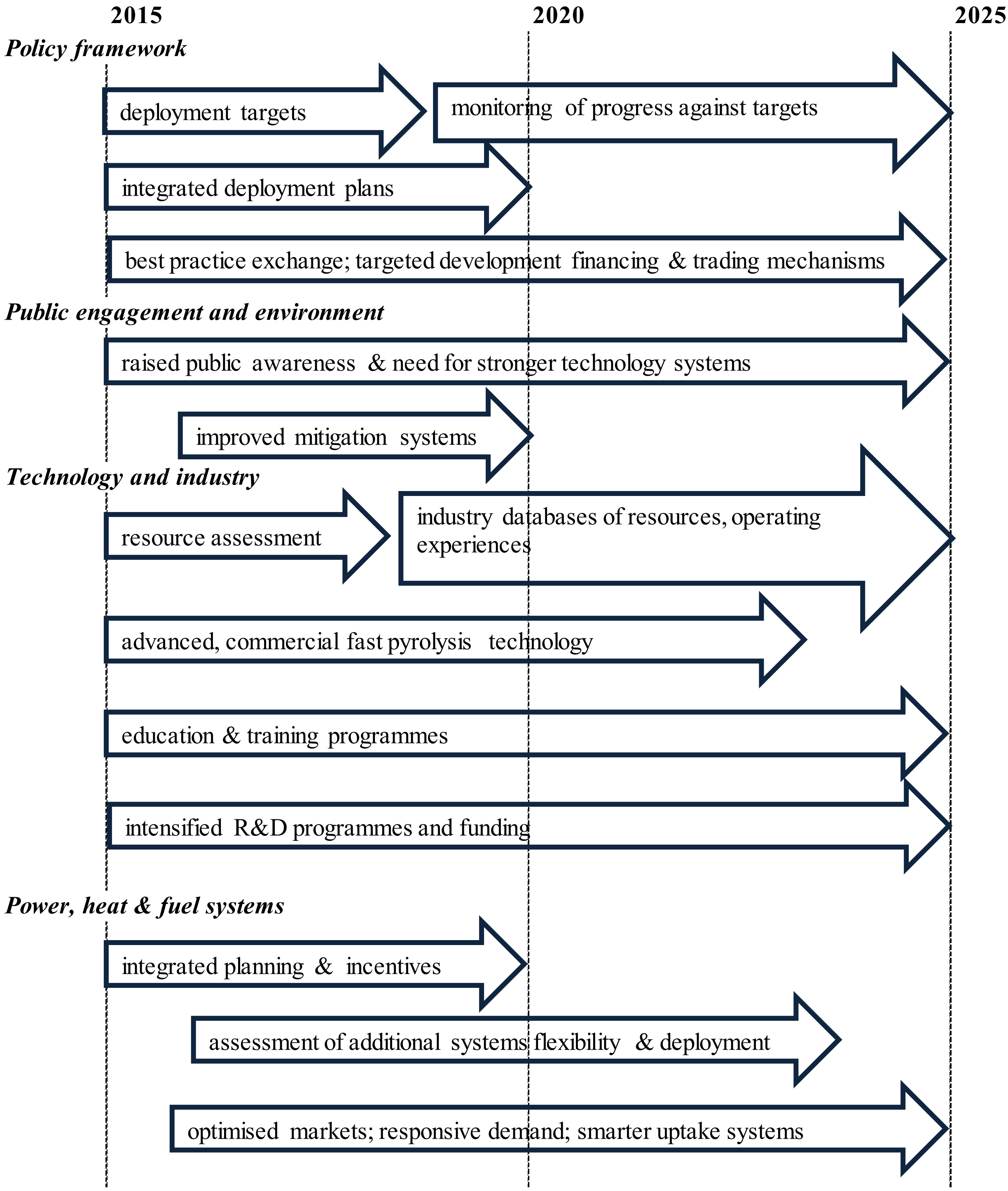

Figure 10-1 Diagram on the roadmap process for fast pyrolysis technology development and deployment in Namibia and South Africa

10.2.3 Existing institutions and implementation agencies identified as important stakeholders

To introduce fast pyrolysis technology in Namibia and South Africa, a number of research, development, accreditation and certification institutes and materials testing laboratories are available from whom knowledge and partnerships could be sought. This list also includes the state owned enterprises which are to consider bioenergy for future supply of electricity and/or liquid fuels. Project funding (though limited) has become available for existing institutions to carry out duties of research, development, standardisation and certification as well as studying the feasibility for commercial implementation. Namibian institutions of similar kind or dedication are available at a limitied scale. The South African institutions and systems are listed below; these may serve the Namibian market too:

- National Energy Regulator of South Africa (NERSA)
- National Research Foundation (NRF)
- Central Energy Fund (CEF)
- South African National Energy Research Institute (SANERI) (Pty) Ltd
- Biofuels Research Chair at the University of Stellenbosch
- Carbon Sequestration Leadership Forum (CSLF)
- Council for Scientific and Industrial Research (CSIR)
- Nuclear Energy Corporation of South Africa (Pty) Ltd (NECSA)
- Palindaba Analytical Laboratories (Pty) Ltd
- South African National Accreditation System (SANAS)
- South African Timber Auditing Services (Pty) Ltd (SATAS)
- SGS (Pty) Ltd – (standards auditing and certification)
- South African Bureau of Standards (Pty) Ltd (SABS)
- Institute for Thermal Separation Technology at the University of Stellenbosch;
- Petronet
- PetroSA
- SASOL
- South African Petroleum Industry Association (SAPIA)
- ESKOM and ESKOM Demand Side Management (DSM)
- Electricity Distribution Industry (EDI) Holdings
- Energy Intensive Users' Group (EIUG): South Africa

- Southern African Power Pool (SAPP); Namibia is a member

To revitalise initiatives for bioenergy also based on converting plant biomass via fast pyrolysis to electricity (or commodity chemicals), the following initiatives or organisations may be of assistance:

- Sustainable Energy Society of Southern Africa (SESSA)
- International Energy Agency (IEA): Bioenergy
- World Council for Renewable Energy
- World Energy Council - Energy for Sustainable Development
- Renewable Energy and Energy Efficiency Partnership (based on Johannesburg Plan of Action which resulted from the United Nations 'World Summit on Sustainable Development')
- Energy Information Administration
- International Energy Foundation (IEF)
- Several European and north American initiatives (e.g., Bioenergy Research Group (UK), PyNe (pan-European and North American), Carbon Trust (UK)

In Namibia, the institutions assisting and concerned with renewable energy initiatives (similar to those in South Africa) are limited. The ones listed below are most relevant to the development of, for example, new renewable energy technology development in Namibia:

- Desert Research Foundation of Namibia (DRFN); a non-governmental organisation that piloted the encroacher-bush 0.25 MW electricity equivalent gasifier between 2006 and 2010
- Renewable Energy and Energy Efficiency Institute (REEEI)
- Electricity Control Board (ECB)
- Nampower Ltd (the national bulk power generation and transmission company)
- Namcor Ltd (the national bulk fuel storage and distribution company)
- Regional Electricity Distributors (REDs)
- Several private sector companies, focused on solar energy.

The latter lists may not be all inclusive but is intended to assist with at least gathering appropriate information and supplying vital data for further analysis.

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