A MULTIPLE SCENARIO ANALYSIS INTO THE POTENTIAL FOR BIOETHANOL PRODUCTION FROM MAIZE IN SOUTH AFRICA

by

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ABSTRACT

Smith, M., 2008: A multiple scenario analysis into the potential for bioethanol production from maize in South Africa. M.Sc. Thesis (Unpublished), University of Johannesburg, Auckland Park, 126pp.

Biofuels have the potential to reduce a country's dependence on imported oil, to ensure diversity of energy sources, to increase the availability of renewable energy sources and to address global environmental issues. In recognition of the potential benefits of the production and use of biofuels, the Department of Minerals and Energy released the *Draft Biofuels Industrial Strategy* in December 2006 with the aim to increase the use of biofuels in South Africa to replace 4.5% of conventional transport fuels by 2013.

However, there are several barriers that need to be overcome before South Africa can establish a large-scale biofuel industry to achieve the DME's biofuel target. This includes environmental barriers, such as the availability of land for the cultivation of biofuel feedstocks and potential threats to food security. This study focuses on these environmental barriers and aims to determine the potential for bioethanol production from maize in South Africa to 2013.

To this purpose, a bioethanol potential model is developed to simulate the potential for bioethanol production from maize in South Africa between 2008 and 2013. The model incorporates four key elements that all impact on the availability of maize for bioethanol production, namely: maize demand; maize supply; the demand for maize as biomaterial; and the available land area for the cultivation of maize.

The study makes further use of the scenario planning method to determine the potential for bioethanol production from maize in South Africa. Four unique bioethanol potential scenarios are designed and simulated within the bioethanol potential model developed for this purpose. Each scenario plays out a different storyline for the future social, economic and natural environment that will impact on the availability of maize for bioethanol production.

The results of the bioethanol potential scenario simulations show that South Africa will be able to produce enough maize to meet the DME's biofuel target of 1.2 billion liters of bioethanol for all scenarios between 2009 and 2010. From 2011 onwards, the bioethanol potential decreases below the DME's target value in both the worst case and rapid change scenarios.

The study concludes that the production of bioethanol from maize in South Africa will have various social, economic and environmental consequences for the country's agricultural sector. The depletion of domestic maize supplies will seriously threaten food security and consequently, increase the country's dependence on maize imports. This will not only affect the country's maize producing regions, but spread throughout South Africa as the demand for agriculturally productive land for maize production increases. Domestic food security is therefore at risk and South Africa will have to resort to other energy technologies to achieve a sustainable and renewable energy future for road transport.

CHAPTER 1
INTRODUCTION

> *"Energy is the lifeblood of our society and economy. We need it to cook, to heat and cool our homes, to travel, and to work." (Hamilton, 2002:xiii).*

1.1 Background

Humans have three basic needs: food, water and shelter. These needs cannot be met without energy. "We need it to cook, to heat and cool our homes, to travel…" (Hamilton, 2002:xiii) and it is therefore no surprise that the supply and consumption of energy has played a pivotal role in the development of human civilisation (Smil, 2000; Afgan *et al*., 1998:235; Amigun *et al*., 2007:2).

What would happen when the world's conventional energy resources are exhausted? There is no doubt that the fabric of human society would collapse (Dincer, 2000:157). This threat has been the prime mover in the search for renewable and alternative energy sources. Secondary to this is the global awareness of the adverse environmental impacts inherent in energy produced from non-renewable sources (Agarwal, 2007:234; Marrison & Larson, 1996:337; Mock *et al*., 1997:308), including indoor and outdoor air pollution, acid precipitation, stratospheric ozone depletion and climate change (Dincer & Rosen, 1999:429; Abbasi & Abbasi, 2000:121; Wang & Schimel, 2003).

Theoretically, renewable energy sources provide the ideal solution to these problems and include biomass, solar, wind, geothermal and hydro energy (Martinot *et al*., 2002:310). The production of energy from renewable sources has the potential to address major environmental issues, to postpone the depletion of finite energy sources and to increase long-term energy security (Dincer, 2000:158; Salameh, 2003:41). Most governments have recognised these potential benefits of renewable energy and have formulated some type of renewable energy policy to promote its use. For instance, in the *Green Paper – Towards a European Strategy for the Security of Energy Supply,* the European Commission aims to substitute 20% of traditional fuels with renewable fuels by 2020 (EC, 2000).

South Africa formulated an *Energy White Paper* in 1998, with the objectives to increase access to affordable energy services; stimulate economic development and growth; manage the environmental and health effects of energy generation; and to secure the supply of energy through developing a diversity of energy sources (DME, 1998, Chapter 5). However, this document did not specifically address the role of renewable energy and six years later the *White Paper on Renewable Energy Policy* was published. The target set in the *Renewable Energy Policy* for energy from renewable sources is 10 000 GWh, or 4% of South Africa's total energy supply, by 2013 (DME, 2004:ix). The Department of Minerals and Energy (DME) further plans that biofuels will contribute 75% to the national renewable energy target (DME, 2006a:9).

Biofuels have the potential to reduce a country's dependence on imported oil, ensure diversity of energy sources, to increase the availability of renewable energy sources and to address global environmental issues (IEA, 2006; Cortez *et al.*, 2003:509; Tait, 2005). In recognition of the potential benefits of biofuel use and production, the DME released the *Draft Biofuels Industrial Strategy* in December 2006 with the aim to increase the use of biofuels to replace 4.5% of conventional transport fuels by 2013.

From a critical point of view, the *Draft Biofuels Industrial Strategy* (DME, 2006a) raises several issues, of which only a few are: *What are the impacts of biofuel production on South Africa's social, economic and natural environments? Does South Africa have sufficient agricultural resources to sustain a large-scale biofuel* *programme? Will a reduction in the annual carry-over stock threaten domestic food security? And what is the DME's biofuel target after 2013?*

1.2 Problem statement

There are four main types of barriers to the production of biofuels in the world today: environmental; economic and financial; institutional and legislative; and socio-political barriers (Moreira, 2003:2). It must be noted that these barriers are interrelated and this creates a challenge for policy formulators (Prasad & Visagie, 2005:37). In fact, the implementation of biofuel programmes "…are tightly bound up with a host of local and international factors, including national energy policies, national security policies, competing interests within the energy, agriculture and transportation sectors, and the international markets for gasoline, sugar, and lead additives." (Thomas & Kwong, 2001:1142).

This study will concentrate on the primary environmental barrier of biofuel production, which is land availability and food security. Global studies by Yamamoto *et al*. (1999 and 2000) established that the land area that is available for the production of energy crops is very limited, and further restricted to specific regions with suitable climatic and soil properties (Walsh *et al*., 2003:318). Biofuel production must also compete with other land uses, such as for grazing, forestry, urban settlements, nature conservation (Kheshgi *et al*., 2000:201; Lal, 2005:576) and most importantly, for the production of food. Frondel and Peters (2006:3) state that it is apparent "…that the promotion of biofuels requires huge amounts of arable land that is also needed for traditional purposes such as food production…", thus seriously threatening domestic food security (Silveira, 2005).

The DME has recognised that biofuel production should not put domestic food security at risk (DME, 2004:17) and South African energy and development corporations have therefore stated the need to determine the location, available hectares and yields of biofuel feedstocks, in order to establish the potential supply of biofuels in South Africa (EDC & IDC, 2006:30).

The problem statement of this study, formulated as a question, is therefore as follows: *What is the future potential for bioethanol production from maize in South Africa to 2013 under different social, economical and environmental conditions?*

1.3 Objectives

Specific objectives of this study are to:

- Provide the reader with a basic understanding of biofuels by reviewing relevant and recently published biofuel literature;

- Develop a model for determining the potential for bioethanol production from maize, taking into account the social, economic and environmental conditions in South Africa;

- Gather and analyse data on the social, economic and environmental factors that influence the potential for bioethanol production from maize in South Africa;

- Develop different future scenarios in which the production of bioethanol from maize in South Africa could play out;

- Interpret the results taking into account the objectives of the *Draft Biofuels Industrial Strategy* (DME, 2006a) and perform a sensitivity analysis to determine which social, economic and environmental factors have the greatest impact on the potential for bioethanol production from maize;

- Compare possible alternatives to achieving a more sustainable energy future for road transport in South Africa;

- Draw conclusions and summarise the results of this study; and

- Recommend further areas for biofuel research in South Africa, in order to achieve a sustainable and renewable energy future for road transport in South Africa.

1.4 Framework

A logical framework was designed to facilitate the investigations of this study. At the same time, the framework informs the reader about the course to be followed in order to achieve the eight objectives mentioned above. This framework is represented as a diagram in Figure 1.1 and will be described below.

Chapter 1 is aimed at informing the reader about the context of the study. The chapter further provides a problem statement and lists the eight objectives to be achieved throughout the rest of the study.

Chapter 2 presents the reader with information in order to gain a general understanding of bioenergy, biofuels and their advantages and disadvantages. Recently published biofuel literature is reviewed to set the scene for current and future biofuel research.

Chapter 3 provides a background to the methodology of this study and defines important concepts to be used in further chapters. A bioethanol potential model is developed in order to determine the availability of maize for bioethanol production and consequently, the potential for bioethanol production from maize in South Africa.

Chapter 4 aims to implement the bioethanol potential model through the simulation of four bioethanol potential scenarios. A sensitivity analysis is also conducted to determine which of the input factors of the bioethanol potential model contribute most to variability in the results.

Chapter 5 offers insight into the possible alternatives to achieving a more sustainable energy future for road transport in South Africa, including bioethanol production from sugar cane and improvements in energy efficiency in road transport.

Chapter 6 summarises the key findings, describes the limitations of the study and identifies areas that need further research.

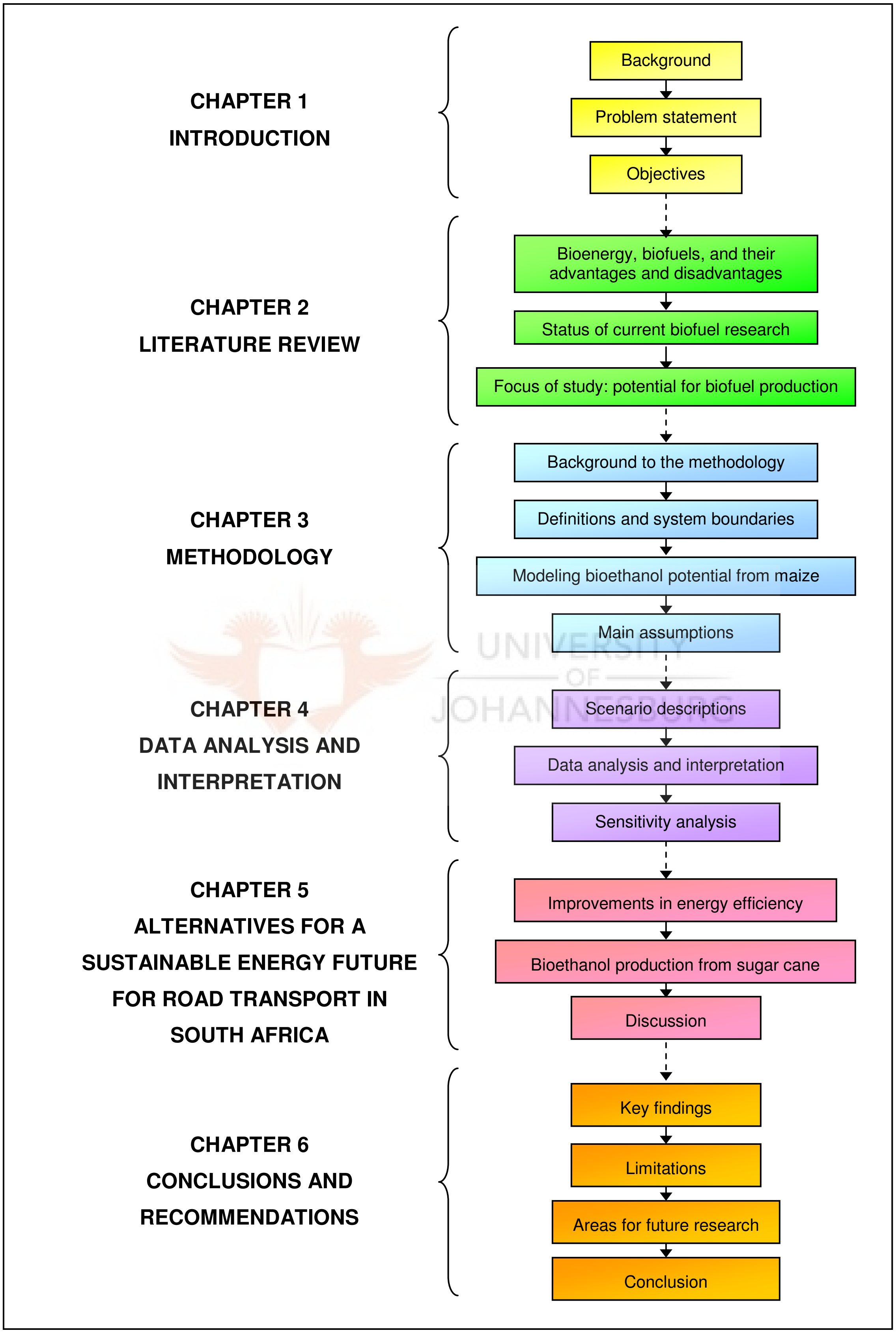

Figure 1.1: Diagrammatic framework of the study

CHAPTER 2
LITERATURE REVIEW

"Biomass has the potential to become one of the major global primary energy sources during the next century, and modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development in industrialized countries as well as in developing countries." (Berndes et al., 2003:1).

2.1 Introduction

Energy has been generated from biomass since the beginning of human civilisation (Hoogwijk *et al*., 2005:225; Hall & House, 1995:38). Today, biomass is still a major energy source in many developing countries, providing up to 80% of the total energy supply in some of these countries (Omer, 2002:526; Ludwig *et al*., 2003:23). In the search for renewable and alternative energy sources, many world governments, including South Africa, have begun to investigate biomass as a potential energy source for the future (Modi *et al*., 2005). This includes investigations into the conversion of biomass into electricity and liquid fuels for transportation (Hoogwijk *et al*., 2005:226).

The aim of this chapter is twofold: The first is to present the reader with a general understanding of bioenergy and biofuels, and the role they could play in fulfilling future energy demands. The second is to set the scene for present and future biofuel research, by reviewing recently published biofuel literature.

2.2 Bioenergy, biofuels, and their advantages and disadvantages

Bioenergy and biofuels are interrelated concepts that can be easily confused and misunderstood. The aim of this section is to explain what bioenergy and biofuels are, as well as to describe their comparative advantages and disadvantages.

2.2.1 Bioenergy

Bioenergy can be defined as "…renewable energy produced from biomass, such as wood and wood wastes, agricultural crops and wastes, or municipal and industrial wastes…" (Cleveland & Morris, 2006:41) and it includes two main types. The first type, traditional bioenergy, is the burning of biomass and charcoal derived from biomass for cooking and heating in rural households. However, this form of bioenergy is characterised by very low energy efficiency (Demirbaş, 2004:226). Improved energy efficiency is obtained in the second type, modern bioenergy, by converting biomass into liquid biofuels, biogas and electricity (Hall & House, 1995:37).

The use of bioenergy has a number of benefits: it is renewable; results in zero net atmospheric CO_2 emissions, but only if produced sustainably; when converted it is available in gaseous, liquid and solid states; and it can be produced domestically, thus promoting energy security (Best & Christensen, 2003:8). These benefits allow bioenergy to play an increasingly important role in the energy and climate-change strategies of developed and developing countries (Ericsson & Nilsson, 2006:1).

Similarly, the South African Department of Minerals and Energy (DME) has put bioenergy, in particular biofuels, at the top of their renewable energy priorities list (DME, 1998:80; DME, 2004:14; DME, 2006a:5). For instance, the DME plans that biofuels will contribute 3% to South Africa's total energy supply by 2013 (DME, 2006a:9).

2.2.2 Biofuels

The *Dictionary of Energy* (Cleveland & Morris, 2006:40) defines biofuels as "…any solid, gaseous, or liquid fuel obtained from biomass." For the purpose of this study, biofuels are defined as liquid fuels produced from biomass for use in the transportation sector (Bomb *et al*., 2007:2256). These fuels can be produced from virtually any type of biomass, as classified in Table 2.1, including: energy crops; agricultural and forestry residues; animal manure; sewage sludge; and wastes (Van Thuijl *et al*., 2003:8).

Table 2.1: Classification of biomass types for the production of biofuels (Source: Van Thuijl *et al*, 2003:8)

Classification	Type of resource	Example
Energy crops	Lignocellulosic crops	Poplar, willow, eucalyptus
	Oil crops	Sunflower seeds, soya beans, rapeseed, olive kernels, Calotropis procera
	Herbaceous crops	Miscanthus, switchgrass, common reed, reed canarygrass, giant reed, Cynara cardunculus
	Sugar crops	Sugar beet, sugar cane, sweet sorghum, sugar millet, Jerusalem artichoke
	Starch crops	Maize, wheat, corn cobs, barley, potatoes, amaranth
	Other	Flax, hemp, tobacco stems, cotton stalks, kenaf
	Aquatic plants	Algae
Residues	Forestry residues	Wood residues, forest thinnings
	Agricultural residues	Straw, sugar beet leaves, residue flows from bulb sector, orchard residues, prunings
	Wood processing residues	Wood chips, sawdust, residue wood
	Construction residues	Demolition wood
	Food industry residues	Swill, residue flows from food and luxury products industry, tallow
	Roadside hay	Grass
Manure	Solid manure	
	Liquid manure	
Waste	Garden, fruit and vegetable waste	
	Dry and wet organic waste	

The type of biofuel produced not only depends on the biomass feedstock used, but also on the conversion process used. As illustrated in Figure 2.1, bioethanol is produced through the fermentation of sugar derived from sugar and starch crops, as well as lignocellulosic biomass. Biodiesel is produced through the esterification of oil extracted from oil plants and animal fat, or the hydro treating and refining of bio oil derived from lignocellulosic biomass. A variety of liquid and gaseous biofuels, including hydrogen, methanol, di-methyl-ether (DME), Fischer-Tropsch diesel (FT-diesel) and syngas, are produced through the gasification or anaerobic digestion of lignocellulosic biomass. Lastly, vegetable oil can be used directly as biofuel in specially designed diesel engines (Agarwal, 2007:237).

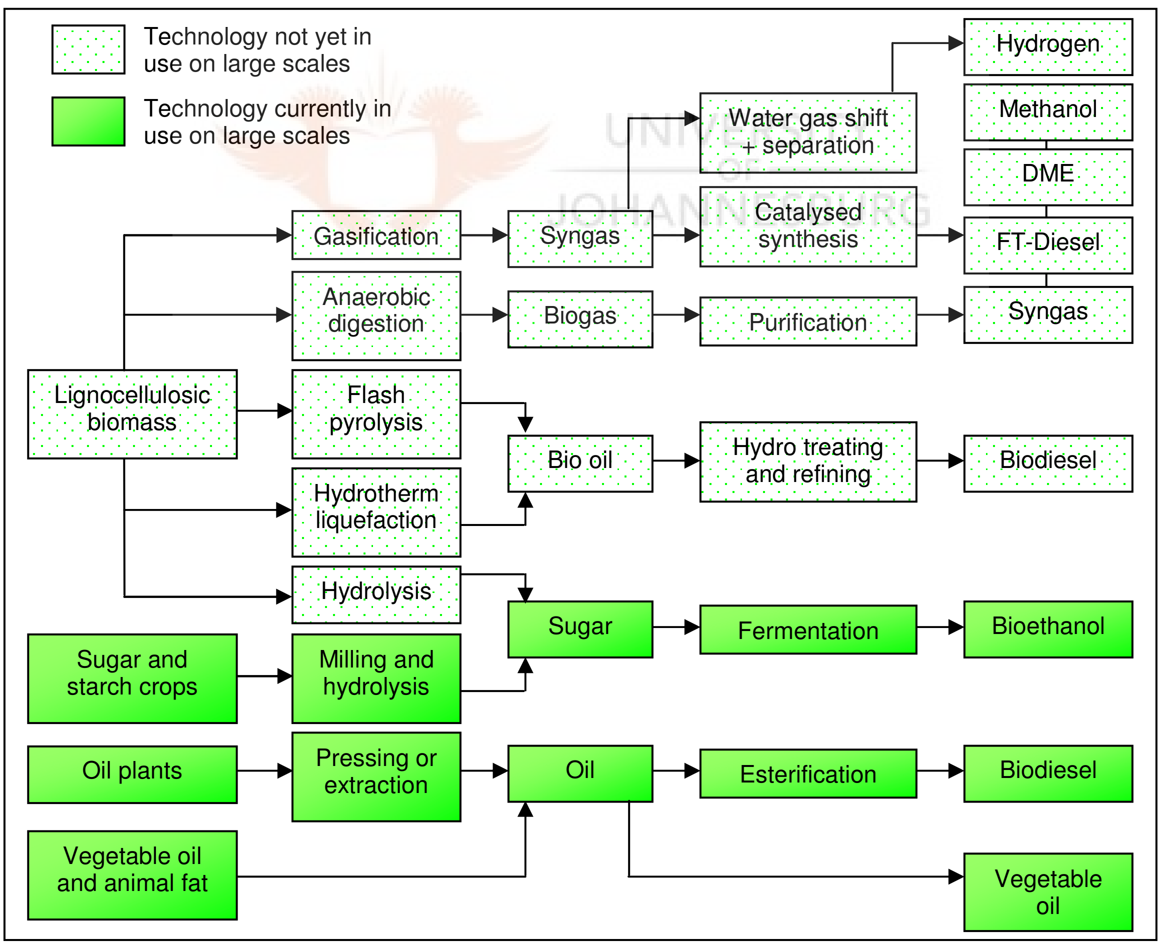

Figure 2.1: Types of biofuels, biomass feedstocks and conversion processes (Source: Agarwal, 2007:237)

Biomass feedstocks and conversion technologies remain expensive and large-scale biofuel production is currently restricted to bioethanol from sugar and starch crops and to biodiesel from oilseeds (Agarwal, 2007:237; Von Blottnitz, 2007). Biofuels that are not currently in mass production include hydrogen, methanol, di-methyl-ether and biogas from lignocellulosic biomass, and vegetable oil from oilseed crops (Quirin *et al.*, 2004:15).

Detailed discussions of the various biofuel conversion processes are beyond the scope of this study and can be found in the studies by Karaosmanoğlu *et al.* (1999), Hamelinck and Faaij (2002), Van Thuijl *et al.* (2003) and Demirbaş (2007).

2.2.3 Advantages and disadvantages

There are both advantages and disadvantages to using and producing biofuels. They can further be divided into three categories, namely environmental, technical and resource-related advantages and disadvantages. A summary of these aspects is presented in Table 2.2.

The section does not, however, aim to weigh the positive and negative aspects of biofuels. The subjectivity of weighing the advantages and disadvantages of biofuels makes it difficult to determine their overall sustainability (Berthiaume *et al.*, 2001:257), although such an environmental and sustainability review is available in Niven (2005).

2.2.3.1 Environmental

- *Advantages*

During the combustion of biofuels the same amount of CO_2 absorbed by plants during photosynthesis and converted to organic material is released into the atmosphere (Cortez *et al.*, 2003:511). Theoretically, this means that there is no net increase of CO_2 in the atmosphere. However, life-cycle analyses (see Section 2.3.2) must be done to quantify the amount of CO_2 emitted during the biofuel production phase (Quirin *et al.*, 2004:2).

Biofuels contain little or no sulphur compared to fossil fuels (Stilbeek, 2006:5), thus reducing the total amount of SO_2 emissions and the formation of harmful acid precipitation (Cadenas & Cabezudo, 1998:91; Williamson & Badr, 1998:195). Also, biofuels are oxygen rich and less carbon monoxide, volatile organic compounds (VOCs), particulate matter and aromatics are produced during combustion (Stilbeek, 2006:5; Tashtoush *et al.*, 2006:2).

A further advantage is that biodegradation of biofuels occurs twice as fast as with petroleum fuels (Zhang *et al.*, 1998:13; Zhou *et al.*, 2003:4; Williamson & Badr, 1998:202).

- *Disadvantages*

Biofuels are produced from biomass which contains considerable amounts of nitrogen. Thus, during the combustion of biofuels, NO_x and aldehydes are released into the atmosphere (Cadenas & Cabezudo, 1998:91). In fact, NO_x emissions are up to 30% higher than with the combustion of petroleum fuels (Stilbeek, 2006:9).

Blending biofuels with petroleum fuels raises the blended fuel's volatility, increasing ozone-causing evaporative emissions and inhibiting biodegradation of petroleum contaminants, such as benzene, toluene, ethyl-benzene and xylenes (Niven, 2005:543).

2.2.3.2 Technical

- *Advantages*

Bioethanol and biodiesel can be used in conventional engines, with little or no alterations necessary (Bomb *et al*., 2007:2256). A further advantage is that they can be blended with petroleum fuels or used in pure form (Cadenas & Cabezudo, 1998:85; Kheshgi *et al*., 2000:214). Bioethanol is an octane-enhancing additive and when added to fossil petroleum fuel it prevents detonation in vehicle engines (Garba *et al*., 2006:173).

Biodiesel has a higher combustion quality than petroleum derived diesel and this increases the power output of vehicle engines up to 9% of that obtained by engines run with petroleum diesel (Williamson & Badr, 1998:191; Bomb *et al*, 2007:2258) and reduces harmful smoke emissions (Van Thuijl *et al*., 2003:11; Garba *et al*., 2006:169).

- *Disadvantages*

Unfortunately, some biofuels are known to harden plastics, strip paint and corrode metals and alloys in vehicle engines (Williamson & Badr, 1998:192). The consequent corrosion of metal storage facilities can result in leakage into underground water courses (Niven, 2005:542).

When using biofuels, one must change fuel filters frequently, for the biofuels can dissolve sediments in fuel tanks, lines and filters (Garba *et al*., 2006:175), resulting in an increased concentration of impurities in the fuel.

2.2.3.3 Resource related

- *Advantages*

There are four main advantages related to the production phase of biofuels. Firstly, the cultivation of energy crops can be beneficial to degraded agricultural land: energy crops have the potential to sequester carbon in the soil and biomass. Secondly, biofuel production creates new markets for agricultural surpluses (Raneses *et al*., 1999:160). Thirdly, small quantities of biofuels can be produced with very simple equipment and they are easily transportable (Stilbeek, 2006:5). Lastly, there are several marketable byproducts produced from most biofuel production processes. For instance, both methanol and glycerine are recovered from the biodiesel production process. The methanol can be sold or reused, while glycerine can be sold to cosmetic and pharmaceutical companies (Van Thuijl *et al*., 2003:11).

- *Disadvantages*

There are three main disadvantages related to the production phase of biofuels. Firstly, the costs of producing biofuels are in most cases higher than the production of fossil fuels (Zaldivar *et al*., 2001:18). Only when using widespread and abundant agricultural residues are the production costs lower (Quirin *et al*., 2004:29).

Unfortunately, the removal of crop residues for the production of biofuels can have severe impacts on soil fertility (Lal, 2005:576). Secondly, the cultivation of energy crops places pressure on limited agricultural resources and biodiversity (Stilbeek, 2006:12), while fertiliser use contributes to the eutrophication of water resources (Berthiaume *et al*., 2001:262; Kim & Dale, 2005:438). Lastly, large areas of land are required for the production of biofuels (Kheshgi *et al*., 2000:230). For instance, to produce 1 billion liters of biodiesel annually, approximately 2 150 km^2 of oil palm or 10 700 km^2 of rapeseed will have to be planted (Stilbeek, 2006:11). This can lead to the destruction of sensitive ecosystems, including tropical rainforests, for the cultivation of energy crops (Pearce, 2005).

2.3 Status of current biofuel research

This section aims to set the scene for current and future biofuel research. Three primary biofuel research areas were identified from the literature reviewed, namely:

- Cellulosic bioethanol;
- Life-cycle assessments; and
- Reviews of past and present biofuel programmes.

As mentioned in the problem statement, the focus of this study is on the potential production of biofuels, specifically bioethanol from maize, in South Africa and further discussions therefore emphasise bioethanol as biofuel.

Bioethanol is a "…clear, colourless, flammable, oxygenated hydrocarbon with the chemical formula C_2H_5OH." (Berg, 1999). According to Cleveland and Morris (2006:40) bioethanol is a "…liquid fuel consisting of ethanol produced from biomass…"

It can be produced from three types of biomass: (1) simple sugars found in sugar cane, sugar beet, molasses and fruit; (2) starch found in grains and potatoes; and (3) cellulose found in woody and herbaceous crops, agricultural residues, wood, organic municipal solid wastes and paper (Cardona & Sánchez, 2006:2447).

Table 2.2: A comparison of the advantages and disadvantages of biofuels

Advantages	Disadvantages
Environmental	
Carbon neutral	Higher NO_x emissions
Reduces the formation of acid rain	More aldehydes produced
Lower production of aromatics	Blending raises fuel volatility
Lower carbon monoxide emissions	Potential leakage to underground water
Lower volatile organic compounds emissions	Inhibits biodegradation of fuel contaminants
Lower particulate matter emissions	
Biodegradable	
Technical	
Used in conventional vehicle engines	Hardens plastics
Blended or used in neat form	Strips paint
Higher combustion efficiency	Corrodes metals and alloys
High octane rating prevents knocking	Dissolves sediments in the fuel tank
Higher cetane number	
Lower viscosity	
Resource related	
Potential to enhance soil fertility	Higher costs involved
Sequesters carbon in the soil and biomass	Destruction of tropical rain forests
Creates new markets for agricultural surpluses	Removal of crop residue can negatively impact on soil fertility
Small quantities can be produced	Pressure on limited agricultural resources
Produced with simple equipment	Negative effects on biodiversity
Easily transportable	Eutrophication of water resources
Byproducts can be reused	Large areas of land are required
	Destruction of sensitive ecosystems

Technologies to convert simple sugars and starch to bioethanol have been commercially used for many years (Demirbaş, 2005:328). The production of bioethanol from cellulosic biomass remains expensive and none of the conversion technologies for producing bioethanol from cellulose have been applied at a commercial scale (Wyman, 1999:190; Cardona & Sánchez, 2007:1; Demirbaş, 2005:328). A great deal of biofuel research is therefore currently focused on developing processes to reduce the costs of cellulosic bioethanol (Nieves *et al*., 1998; Eriksson *et al*., 2002; Ballesteros *et al*., 2004; Kristensen *et al*., 2007).

2.3.1 Cellulosic bioethanol

Cellulosic (lignocellulosic) bioethanol is produced from cellulosic biomass which consists of cellulose, hemicellulose and lignin. Cellulosic biomass, such as woody and herbaceous crops, is generally widespread and abundant. These crops are widely available and therefore relatively inexpensive feedstocks for bioethanol production (Kadam, 2002:374; Demirbaş, 2005:329). In fact, Wyman (1999:190) states that "…no other sustainable option for production of transportation fuels can match bioethanol made from lignocellulosic biomass."

The production of bioethanol from cellulosic material such as agricultural wastes also provides a solution to the problem of agricultural waste disposal (Wyman, 1999:193) and decreases greenhouse gas emissions from the burning of agricultural wastes in the field.

Unfortunately, the structural characteristics and presence of lignin in cellulosic biomass makes it more difficult to convert to bioethanol (Silverstein *et al*., 2006:2; Öhgren *et al*., 2007:607). Consequently, multidisciplinary research has been done to develop cellulose-to-bioethanol conversion processes. The primary focus of this research is pretreatment processes, and overall process design.

2.3.1.1 Pretreatment processes

The production of cellulosic bioethanol consists of three distinct stages, namely pretreatment, hydrolysis and fermentation (Demirbaş, 2005:333).

The pretreatment stage involves the softening of and mechanical break down of the biomass, in order to make the compounds susceptible to enzymatic attack in the following stages (Del Campo *et al.*, 2006:215; Demirbaş, 2005:333). Pretreatment processes that have received most attention include dilute-acid pretreatment (e.g. Del Campo *et al.*, 2006; Dien *et al.*, 2006; Chen *et al.*, 1996); steam explosion (e.g. Sassner *et al.*, 2007; Öhgren *et al.*, 2007); ammonia fiber explosion (e.g. Holtzapple *et al.*, 1992); lime (e.g. Chang *et al.*, 1996); and biological delignification (e.g. Tabka *et al.*, 2006).

Silverstein *et al.* (2006) compare four pretreatment processes. They find that treatment factors such as temperature and pressure could have a significant effect on the success of each pretreatment process. Eggeman and Elander (2005:2024) expand this comparison to include an additional pretreatment method and find that the cost of the cheapest pretreatment process is usually counterbalanced by high costs during the following phases of production. The two studies mentioned all conclude that any further improvements in pretreatment processes will depend on the optimisation of the subsequent hydrolysis and fermentation stages.

2.3.1.2 Process design

Process design studies aim to reduce the overall costs of bioethanol by utilising modelling tools to optimise the stages and elements of the bioethanol production process (Wooley *et al.*, 1999:795). Some process design studies include all stages and elements of the bioethanol production process (Cardona & Sánchez, 2007; Wooley *et al.*, 1999; Zaldivar *et al.*, 2001). However, other studies focus on only one or two stages and elements of production. For instance, Kristensen *et al.* (2007) investigate the addition of non-ionic detergents and proteins during enzymatic hydrolysis, the second phase of production. They find that these additions lower the amount of expensive enzymes needed during enzymatic hydrolysis, thus lowering the overall costs (Kristensen *et al.*, 2007:894).

On the other hand, Nieves *et al.* (1998) tested the efficiency of different enzymes during enzymatic hydrolysis. The production process can be designed to recover non-fermentable compounds, which can then be used to generate steam and electricity used to power the bioethanol production process. This technology is called Combined Heat and Power (CHP) generation and it is known to lower the overall bioethanol production costs (Reith *et al.*, 2001:8; Reith *et al.*, 2002:4).

It is common practice in process design studies to test the process in the real world. Schell *et al.* (2004), Nguyen and Prince (1996) and Henke *et al.* (2006) monitor the bioethanol production processes using different feedstocks, such as corn fiber, sugar cane and sweet sorghum, and processed sugar and molasses, respectively. A general finding of these studies is that the ultimate success of any biofuel production process depends on the size of, and the amount of biofuel feedstocks processed in, the biofuel plant.

2.3.2 Life-cycle assessments

Life-cycle assessments (LCAs) differ from process design studies in that they go beyond the biofuel conversion process to include an analysis of all stages of biofuel production. As illustrated in Figure 2.2, energy consumption and greenhouse gas emissions occur during all the stages of biofuel production. These stages include the production of energy from fossil fuels and the transport of these fossil fuels, as well as the transport of fertilisers, chemicals, fuels, biomass and co-products itself. Additional energy is consumed during the transport of the biofuel to the consumer market, custom operations on the farm and the production of fertilisers and chemicals.

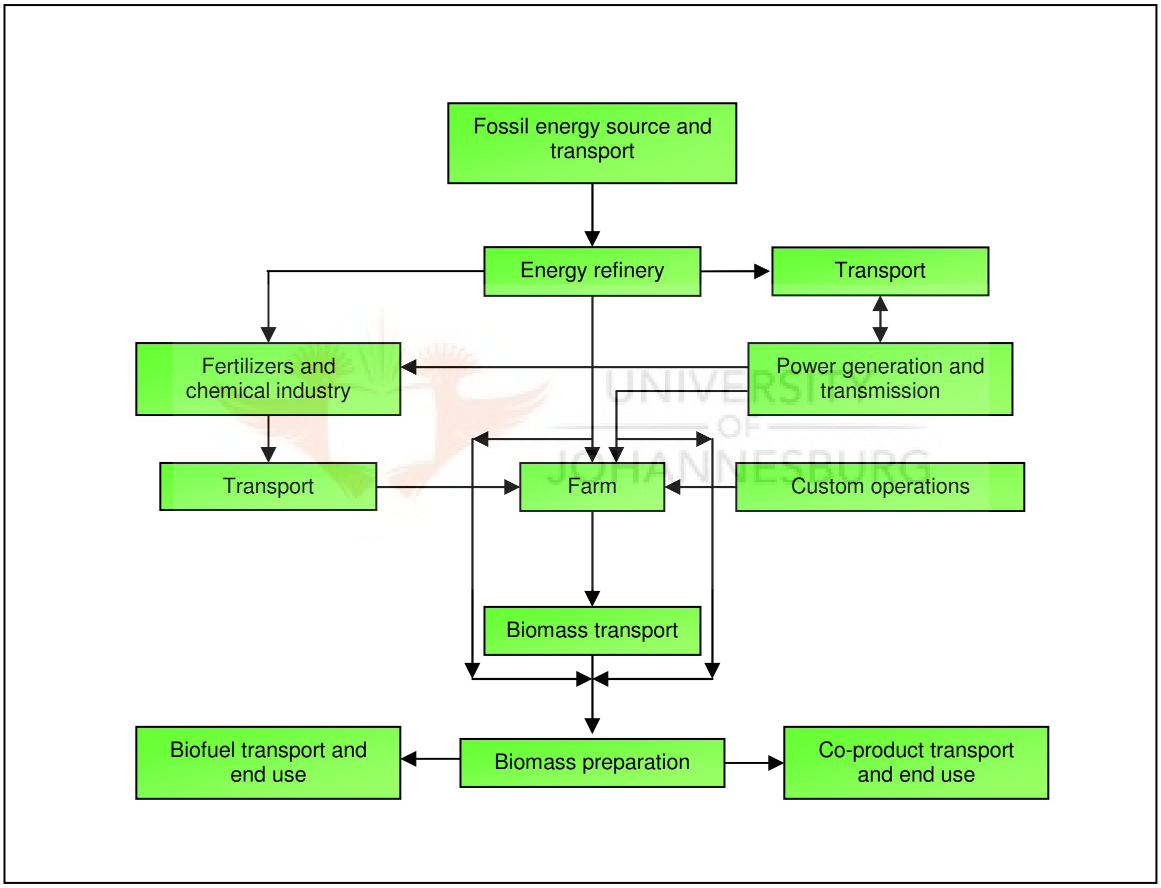

Figure 2.2: Simplified systems flow diagram of a generic biofuel life-cycle
(Source: Adapted from Graboski, 2002:10)

Another important difference is that life-cycle assessments focus primarily on the energy and environmental impacts of biofuel production and mostly ignores economic factors (Quirin *et al.*, 2004). In other words, a life-cycle assessment "…quantifies the energy use, material requirements, wastes, emissions, and potential environmental impacts that are associated with the provision of a product, service, or activity throughout its life-cycle" (Puppan, 2002:108).

The life-cycle assessments reviewed in this section focus on the energy and environmental aspects of bioethanol production and they have been divided into three main categories, namely:

- Energy balances;
- Greenhouse gas (GHG) balances; and
- Qualitative environmental assessments.

2.3.2.1 Energy balances

An energy balance is an "…analytical technique that attempts to account for all energy coming in and going out of a system." (Cleveland & Morris, 2006:142). Prakash *et al*. (1998:1629) define energy balances as the "…net energy yield of the fully developed resource that measures the true value of an energy resource to society." In the context of biofuels, energy balances are used to determine the amount of fossil fuels that can be displaced through the use of biofuels as an alternative to conventional transport fuels (Malça & Freire, 2004:2; Malça & Freire, 2006:3364). It is measured as the net energy gain, which is the difference between the energy contained in the biofuel and the energy used to produce the biofuel (Andress, 2002:1).

Ten studies were found that aim to determine the energy balance of bioethanol from maize. Kim and Dale (2005) determine the energy balance of bioethanol from maize under various cropping systems. They conclude that the bioethanol energy ratio is positive for all cropping systems, thus bioethanol can help save non-renewable energy (Kim & Dale, 2005:438). Graboski (2002:46) limits his energy balance study to include only fossil energy sources and calculated the bioethanol energy ratio as 1.32. In other words, bioethanol produced from maize contains 1.32 times more energy than that used during its production. Advancements in agricultural technologies could result in the achievement of a bioethanol energy ratio of up to 1.4 by 2012 (Graboski, 2002:52).

A review of several maize-based bioethanol life-cycle assessments is available in Andress (2002) and Von Blottnitz and Curran (2007). It must be noted that the results of bioethanol energy balances for maize can vary up to 37% between the different approaches used (Kim & Dale, 2002:7). On the other hand, negative energy balances for bioethanol from maize were determined by Pimentel (2003), Patzek (2004) and Pimentel and Patzek (2005). These studies differ from those with a positive energy balance in that they include additional energy inputs in their energy balance models, such as energy used during the planting and harvesting of maize and the energy used during fermentation and distillation.

Berthiaume *et al*. (2001) propose an alternative method for evaluating the renewability of biofuels, using an exergy-based[1] approach. This approach shows that the analysis of a biofuel's renewability depends on all processes and cycles associated with the production of the biofuel. It also takes into account different forms of energy, as well as varying levels of energy quality. Berthiaume *et al*. (2001:266) show in an exergy-based case study that bioethanol from maize is, in fact, non-renewable.

[1] *Exergy is the maximum amount of useful work (ordered motion) that a system can perform when it is brought into thermodynamic equilibrium with its surroundings by reversible processes (Source: Cleveland & Morris, 2006: 155).*

A sub-category of energy balance life-cycle assessments is the energy renewability efficiency (ERenEF) study, which "…measures the fraction of final fuel energy obtained from renewable sources." (Malça & Freire, 2006:3377). In an energy renewability efficiency study by Malça and Freire (2006:3377) it was found that up to 48% of the energy contained in bioethanol produced from wheat and up to 37% of that in bioethanol produced from sugar beet, is derived from renewable sources.

2.3.2.2 Greenhouse gas balances

The production and distribution of biofuels requires additional inputs of fossil fuels (Curran, 2005:1), as was illustrated in Figure 2.2. Carbon dioxide is thus not only produced during the combustion of biofuels, but also during all the stages of its production and distribution (Prakash *et al.*, 1998:1629). Still, most life-cycle assessments conclude that biofuels are carbon neutral (Quirin *et al.*, 2004:1), resulting in no net increase of CO_2 in the atmosphere.

A study by the National Renewable Energy Laboratory (Tyson, 1993) determined that the use of bioethanol as alternative to petrol could reduce CO_2 emissions by up to 90%. Macedo (1998:81) studied the greenhouse gas balances for the sugar-ethanol industry in Brazil and concluded that bioethanol has helped Brazil reduce their CO_2 emissions by up to 20% per year between 1988 and 1996. Using a different approach, Sheehan (1998) concludes that bioethanol use in the USA could result in a mere 14% reduction in CO_2 emissions by 2015.

2.3.2.3 Qualitative environmental assessments

Only six studies have been assessed in which authors have expanded traditional life-cycle assessments beyond energy and CO_2 emissions, to include additional environmental impacts. For instance, Kaltschmitt *et al*. (1997:130) determined the environmental impacts of ethanol production from sugar beet, wheat and potato in Germany. They found that ethanol production resulted in the conservation of fossil fuel sources and a reduction of greenhouse gas emissions, although the emissions of N_2O and NO_x emissions were higher.

Ethanol production further results in the pollution of ground and groundwater through the use of fertilisers and pesticides during feedstock production, as well as a loss in biodiversity (Puppan, 2002:107). Puppan (2002:112) concludes that the net environmental impacts of biofuel production will depend on the type of agricultural system in use. Reinhardt and Uihlein (2002) draw the same conclusion for ethanol production from sugar beet, wheat and potatoes in other European countries.

The other three studies examined are based on ethanol production from cellulosic biomass. Kadam (2002) determines the impacts of converting bagasse[2] to ethanol in India. The author concludes that ethanol production results in less CO_2, CO, SO_x, NO_x, particulate matter and methane emissions, than burning bagasse in the field. The production of solid wastes is also lower (Kadam, 2002:381). Ethanol production from residual corn stover in the USA have the opposite impacts, resulting in higher CO, NO_x and SO_x emissions, as found by Sheehan *et al*. (2004:139). Tan and Culuba (2002:6) conclude the same for cellulosic ethanol in the Philippines, with the exception of lower NO_x emissions.

[2] *Bagasse is the residue remaining after juice is extracted from sugarcane in a milling process. It can be used as a fuel (Source: Cleveland & Morris, 2006:31).*

2.3.3 Review of past and present bioethanol programmes

One way in which researchers have aimed to determine the future potential of bioethanol as road transport fuel is by evaluating existing large-scale bioethanol production programmes around the world (Cortez *et al*., 2003; Braunbeck *et al*., 1999; Kheshgi *et al*., 2000; Van Thuijl & Deurwaarder, 2006; Rosillo-Calle & Cortez, 1998; Austin *et al*., 2003; Trindade, 2003).

The world's first major bioethanol programme was launched by Brazil in 1975. Proalcool, as the programme was named, was originally an offshoot of the sugar industry aimed at creating alternative uses for sugar surpluses (Cortez *et al*., 2003:512; Rosillo-Calle & Cortez, 1998:115; Berg, 1999). During the 1970s and 1980s the Brazilian bioethanol programme experienced significant growth, due to an increase in world oil prices and related energy shortages. However, world oil prices dropped during the second half of the 1980s, causing stagnation in the industry. Since 1989, annual Brazilian ethanol production has remained constant at around 13 billion liters (Cortez *et al*., 2003:513; Braunbeck *et al*., 1999:496).

According to Cortez *et al.* (2003) bioethanol production was originally promoted in the USA in response to four issues. Firstly, bioethanol production and use could help the USA overcome dependence on imported oil. Secondly, it could boost the agricultural sector and provide a sink for national agricultural surpluses. Thirdly, bioethanol as oxygenate could raise the low octane ratings of petrol after the phasing-out of lead in 1977. Lastly, bioethanol was promoted to lower air pollution (Cortez *et al*., 2003:513). In fact, bioethanol production was boosted in 1990 with the enactment of the *Clean Air Act Amendments* (CAAA), which stipulates that a certain amount of oxygenated fuels should originate from renewable sources, such as bioethanol (Cortez *et al*., 2003:514). Consequently, domestic production of bioethanol from maize grew and amounted to 7.5 billion liters in 2003 (Cortez *et al.*, 2003:514).

The European Union has been promoting the use of biofuels since the beginning of the 1990s. Since 1990 several policies were formulated, including the White Paper, *Energy for the Future: Renewable Sources of Energy* (EC, 1997) and the Green Paper, *Towards a European Strategy for the Security of Energy Supply* (EC, 2000). Finally, in 2003, the EU published their first biofuels-law, the *Directive on the Promotion of the Use of Biofuels or Other Renewable Fuels for Transport* (EU, 2003). Consequently, biofuel production increased dramatically and the total production of bioethanol in the EU reached 404 000 tons in 2004 (Van Thuijl & Deurwaarder, 2006:9).

From the previous discussion it becomes clear that bioethanol production around the world has been the result of dedicated policy actions towards the promotion of energy security; the mitigation of climate change; the management of air pollution; and stimulating growth in the agricultural sector.

2.4 Focus of study: Potential for biofuel production

The two most important factors affecting the potential of bioenergy production in any country are the amount of available land for the cultivation of biofuel feedstocks; and consequently, the availability of biofuel feedstocks (Hall & House, 1995:39).

Studies that aim to determine the potential supply of bioenergy are usually conducted at regional or global levels. For instance, Hall and House (1995:47) estimated the potential supply of biomass for bioenergy in Western Europe and concluded that bioenergy could supply 9 to 13.5 EJ (17-30% of the projected regional energy requirements) by 2050. In Africa, Marrison and Larson

(1996:350) predict a bioenergy contribution of 18 EJ per year by 2025. Global estimations by Yamamoto *et al*. (1999:111) show large global bioenergy potentials of up to 425 EJ by 2100.

On the other hand, Berndes and Wirsenius (1996:928) noted that future requirements for food and biomaterials alone, demands a global increase in bioproductive land. Competition over land would thus restrict the potential of bioenergy globally. However, a review of seventeen bioenergy potential studies by Berndes *et al*. (2003) concludes that it is difficult to compare these estimates, for they utilise different methodologies.

The studies mentioned have two important shortcomings. Firstly, the studies have a global geographical scope, lacking local assessments of biomass productivity (Ericsson & Nilsson, 2006:2). Ericsson and Nilsson (2006) aim to rectify this by determining bioenergy potential at a national level for eight EU member states. Similarly, Tuck *et al*. (2006) establish the current and future distributions of several bioenergy crops, based on local biophysical conditions. Hoogwijk *et al*. (2005:226) use a different approach, calculating the 'geographical potential' of bioenergy, in other words, the global potential of bioenergy at a scale equaling 0.5° by 0.5° on the global geographical grid. The study differs from those previously mentioned in that the authors incorporate food supply and demand issues into their assessment. For this reason, the methodology used by Hoogwijk *et al*. (2005) forms the basis for further investigations, as will be discussed in Chapter 3.

The second important shortcoming is that bioenergy potential is determined collectively, thus the studies do not focus on a specific type of bioenergy, for instance biofuels (Hoogwijk *et al*., 2005:226), which is the focus of this study.

Nine studies were identified that specifically aim to establish the potential supply of biofuels. These studies follow one of two approaches. The first approach is feedstock-specific and concentrates on determining the availability of specific biofuel-feedstocks, e.g. wheat or rapeseed. The second approach is biofuel-specific and focuses on certain types of biofuels, i.e. bioethanol or biodiesel.

The feedstock-specific approach is highly dependent on the ethanol yields of each feedstock. For this purpose, Table 2.3 is included and summarises the composition and ethanol yields of some bioethanol feedstocks. Sugar cane has the highest yield, equaling 0.5 liter of ethanol per kilogram of dry biomass. It can be observed that agricultural residues generally have lower yields than energy crops.

Table 2.3: Composition of energy crops and bioethanol yields (Source: Kim & Dale, 2004:363)

Feedstock	Residue to crop ratio[(1)]	Dry matter (%)	Lignin (%)	Carbohydrates (%)	Ethanol yield (liter per kg of dry biomass)
Maize	1.0	86.2	0.60	73.70	0.46
Maize stover		78.5	18.60	58.29	0.29
Wheat	1.3	89.1	0.00	35.85	0.40
Wheat straw		90.1	16.00	54.00	0.29
Barley	1.2	88.7	2.90	67.10	0.41
Barley straw		81.0	9.00	70.00	0.31
Sorghum	1.3	89.0	1.40	71.60	0.44
Sorghum straw		88.0	15.00	61.00	0.27
Oat	1.3	89.1	4.00	65.60	0.41
Oat straw		90.1	13.75	59.10	0.26
Rice	1.4	88.6	0.00	87.50	0.48
Rice straw		88.0	7.13	49.33	0.28
Sugar cane	0.6	26.0	0.00	67.00	0.50
Bagasse		71.0	14.50	67.15	0.28

Note: [(1)] Defined as ton of crop residue per ton of crop.

2.4.1 Feedstock-specific approach

Potential biofuel feedstocks include energy crops, agricultural and forestry residues, animal manure, sewage sludge and organic wastes (see Table 2.1). Food crops are essential for national food security and thus should not be used in the production of biofuels (Wyman, 1999:195). Consequently, most feedstock-specific studies focus on determining the availability of agricultural residues and wastes to generate biofuels (Kadam & McMillan, 2003; Lal, 2005; Kim & Dale, 2004; Schell *et al.*, 2004).

Approximately 25% of agricultural residues must be left in the field to protect the soil from erosion by wind and water; and another 5% is used as cattle feed, or as bio material in the production of composite products, pulp and paper, and chemicals (Kadam & McMillan, 2003:21). Thus, up to 70% of agricultural residues are available for biofuel production (Lal, 2005:580). Kadam and McMillan (2003:23) determine that 60 to 80 million tons of corn stover are available for biofuel production in the USA each year. However, Lal (2005:582) warns that the continuous removal of agricultural residues from fields could degrade soil fertility and lower agricultural productivity.

Some studies neglect to address the barriers posed by the competitive uses of biomass feedstocks, by considering only wasted crops as a potential bioethanol feedstock. Wasted crops are crops that are lost during the handling, storage and transport phases (Kim & Dale, 2004:362). Kim and Dale (2004:373) determined the availability of wasted crops, such as corn stover, crop straws and bagasse, to produce bioethanol on a global scale. They concluded that approximately 73 million tons of wasted crops are available for biofuel production globally.

The potential of several unconventional biofuel feedstocks have also been investigated, for instance fruit and vegetable solid waste (FVSW) (Gunaseelan, 2004); and thinnings from overstocked forests (Polagye *et al.*, 2007).

Gunaseelan (2004:396) tested the biochemical methane potential of 54 fruit and vegetable wastes and found that mandarin seeds and onion peels yielded the largest volume of methane per gram of feedstock used. In a different study by Polagye *et al*. (2007:118) the authors showed that biofuel production from forest thinnings is cheaper than removing the thinnings to an off-site waste disposal facility.

2.4.2 Biofuel-specific approach

The biofuel-specific approach investigates (1) a certain type of biofuel and (2) consequently identifies several possible feedstocks. For instance, Murphy and McCarthy (2005:160) investigated potential bioethanol production from energy crops and wastes in Ireland. They found that 526 kilotonnes of sugarbeet and 671 000 tons of wastepaper are potentially available to produce 400 million liters of ethanol each year. Annual potential bioethanol production in Africa was determined by Thomas and Kwong (2001:1141) to equal 4 200 million liters of ethanol from sugar cane and 470 million liters from molasses. The greatest potential was identified in South Africa, where a potential 1 500 million liters ethanol from sugar cane and 200 million liters ethanol from molasses are possible. However, maize was not identified as a potential bioethanol feedstock.

These studies are usually conducted at very large geographical scales and this tends to lead to generalised results. Bioethanol programmes are usually dependent on a variety of local and international factors, such as national energy and security policies, competing interest within the energy, agriculture and transportation sectors and international markets (Thomas & Kwong, 2001:1142). All of these factors must be taken into account, irrespective of scale. Thomas and Kwong (2001:1142) therefore propose that determining exact biofuel potentials "…will require carefully designed programs adapted to local conditions."

2.5 Synthesis

Biomass is receiving increasing attention as potential energy source for the future (Ericsson & Nilsson, 2006:1). More specifically, biofuels have been at the centre of many political and energy related discussions over the past few years. The first aim of this chapter was to explain to the reader what bioenergy and biofuels are, and what their environmental, technical and resource related advantages and disadvantages are. The second aim was to set the scene for present and future biofuel research by reviewing relevant literature.

It was explained that biofuels are liquid fuels produced from virtually any type of biomass for use in the transportation sector (Bomb *et al.*, 2007:2256). They have many environmental, technical and resource related advantages, including lower emissions of dangerous air pollutants, their compatibility with conventional vehicle engines and their potential to create new markets for agricultural products. Unfortunately, these advantages are counterbalanced to a certain extent by disadvantages (see Table 2.2), such as the production and emission of toxic aldehydes, lower energy yields and their higher costs (Niven, 2005). The literature review showed that current research efforts focus on enhancing the positive aspects of biofuels, while lowering the environmental and economic costs of biofuel production technologies. One such study focused on quantifying the amount of available land for biofuel production and consequently, the amount of potentially available biofuel feedstocks.

As the focus of this study is the potential of maize as bioethanol feedstock in South Africa, special attention was given to biofuel potential studies. This included an analysis of bioenergy potential studies (Hall & House, 1995; Marrison & Larson, 1996; Yamamoto *et al.*, 1999; Berndes & Wirsenius, 1996; Berndes *et al.*, 2003; Ericsson & Nilsson, 2006; Tuck *et al.*, 2006; Hoogwijk *et al.*, 2005), feedstock-specific studies (Kadam & McMillan, 2003; Lal, 2005; Kim & Dale, 2004; Schell *et al.*, 2004; Gunaseelan, 2004; Polagye *et al.*, 2007) and biofuel-specific studies (Murphy & McCarthy, 2005; Thomas & Kwong, 2001).

While reviewing these studies, two main shortcomings were identified in the approaches followed: Firstly, most of these studies were performed at global geographical scopes and tended to lead to generalised results. Secondly, bioenergy potential was determined collectively, while those studies that did focus on biofuels specifically only considered agricultural residues and organic wastes as potential feedstocks. The approach that showed the highest degree of compatibility with the objectives of this study was that by Hoogwijk *et al*. (2005). Consequently, the approach followed by Hoogwijk *et al*. (2005) was chosen to guide further investigations into the potential of bioethanol production from maize in South Africa.

CHAPTER 3
METHODOLOGY

"The potential assessment that integrates food demand and supply at a detailed geographical level can supply new insights in the spatial and time dynamics of the potential of biomass for energy." (Hoogwijk et al., 2005:226).

3.1 Introduction

One of the main focuses of this study is on the availability of land for the production of biofuels. As mentioned in the problem statement (Section 1.2), the global land area that is available for the cultivation of energy crops is limited and as a result, biofuel production must compete over land used for the production of food (Frondel & Peters, 2006:3). Food demand and supply therefore becomes an essential part of any investigation into the global or regional potential of biofuels (Silveira, 2005). As stated by Hoogwijk *et al*. (2005:226), such an approach that integrates food demand and supply aspects can "…supply new insights in the spatial and time dynamics of the potential of biomass for energy."

The study by Hoogwijk *et al*. (2005) is a principal example of how food demand and supply issues are used to determine bioenergy potential. The aim of this study is to determine the potential for bioethanol production from maize in South Arica. Therefore, the food demand and supply approach of Hoogwijk *et al*. (2005) was chosen to guide the current investigation.

3.2 Background to the methodology

Hoogwijk *et al*. (2005) uses a food demand and supply approach to determine the global potential of bioenergy. To this purpose, the authors define two types of potentials of bioenergy: Firstly, the geographical potential is defined as the maximum amount of biomass that is available for the production of bioenergy, without affecting domestic food supplies. Secondly, the technical potential is the amount of bioenergy that can be generated from the available biomass (Hoogwijk *et al*., 2005:227).

The geographical and technical potential is calculated by taking numerous social, economic and environmental elements into account. As illustrated in Figure 3.1, the available area (A) for energy crop production and the energy crop productivity (Y) are derived from the *Integrated Model to Assess the Global Environment* (IMAGE 2.2). This model was designed to explore future changes in the global environment, including changes in the demand and supply of food crops (IMAGEteam, 2001). Outside IMAGE 2.2., the exclusion factor (a) is introduced to account for the fraction of land that is not available for bioenergy production; while the management factor (MF) accounts for potential increases in energy crop yields due to improvements in agricultural technologies.

The geographical potential (G) is thus defined as:

$$G = \sum_{i=1}^{n} A \times a \times Y \times MF \tag{3.1}$$

Where,

G	=	geographical potential;
A	=	available area for energy crop production;
a	=	exclusion factor;
Y	=	energy crop productivity; and
MF	=	management factor (Hoogwijk *et al*., 2005:230).

The geographical potential (*G*) is simply multiplied by the conversion efficiency (η) of the conversion technology used, to determine the technical potential (*T*).

Technical potential is therefore defined as:

$$T = G \times \eta$$

(3.2)

Where,

T = technical potential;

G = geographical potential; and

η = conversion efficiency.

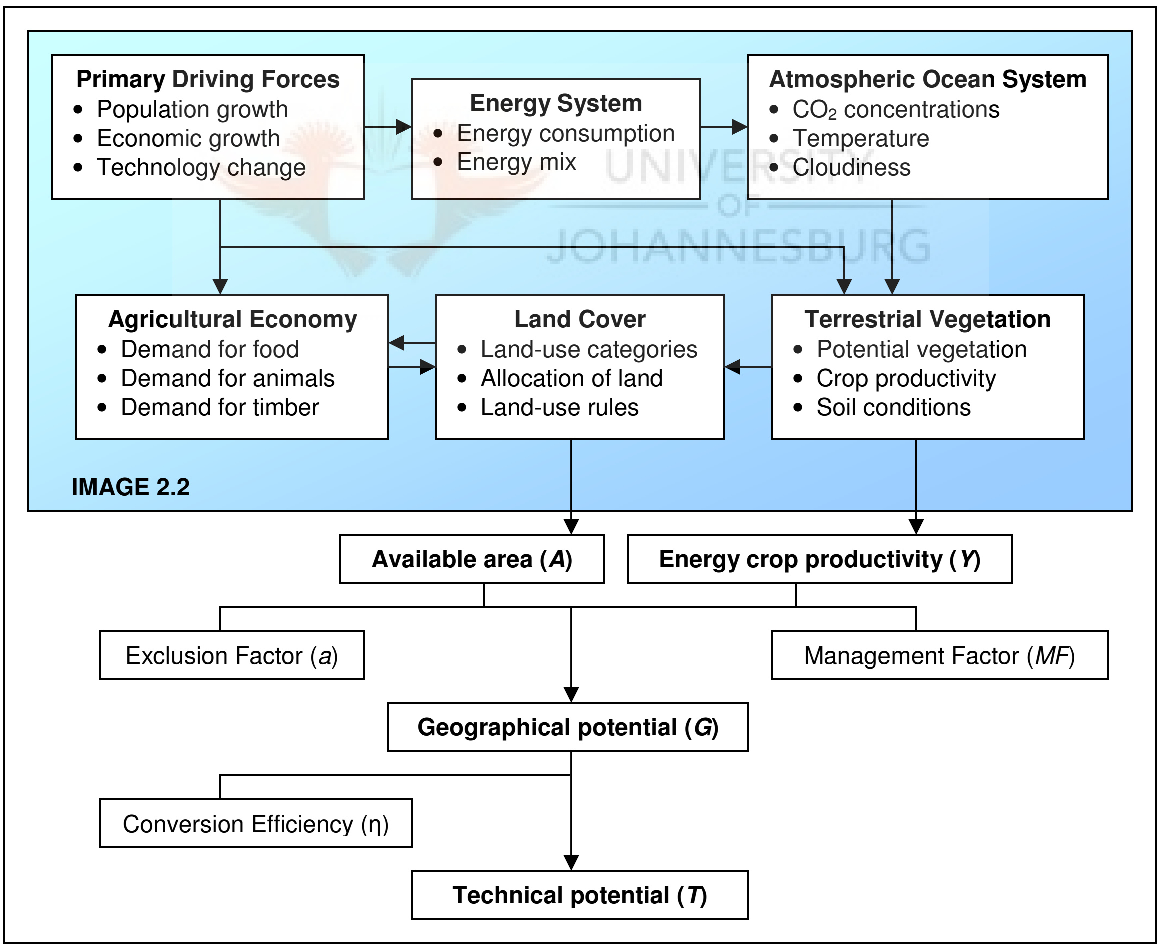

Figure 3.1: Key elements in assessing the geographical and technical potential for bioenergy (Source: Hoogwijk *et al.*, 2005:230)

The key elements identified and outlined in Figure 3.1 were derived from a previous study by Hoogwijk *et al*. (2003), which concluded that the potential availability of biomass for energy is influenced by four main factors, or elements, namely:

- food demand, which is influenced by population size and food consumption trends;
- food supply, which is influenced by the agricultural system in use and the productivity of forest and energy crops;
- alternative uses of biomass, e.g. biomaterials used in the food, textile, pharmaceutical, paper and paint industries; and
- competing land-uses, e.g. grazing, forestry, urban settlements, nature conservation and food production (Hoogwijk *et al*., 2003:131).

Hoogwijk *et al*. (2005) included a sensitivity analysis and found that the type of technology used to produce energy crops is the single most important factor influencing the geographical and technical potential of bioenergy (Hoogwijk *et al*., 2005:248).

Hoogwijk *et al.* (2005) identified two important limitations to their approach. Firstly, the method does not include all of the elements that influence bioenergy potential, for instance the willingness to invest in energy plantations (Hoogwijk *et al*., 2005:252). Secondly, the method includes all forms of bioenergy, including bioethanol, biodiesel and biogas. Elements that are significant to bioethanol production, such as maize and sugar cane harvesting methods, are not distinguished or taken into account.

The next section sets out to identify and define the key elements of this study and to define the potential for bioethanol production from maize in South Africa.

3.3 Definitions and system boundaries

The elements identified by Hoogwijk *et al*. (2005) have been adapted to meet the specific objectives of this study, namely bioethanol production from maize in South Africa. The four key elements are:

- maize demand, which is influenced by population size and food consumption trends;
- maize supply, which is influenced by crop productivity;
- the demand for maize as biomaterial in the food, animal feed, textile, pharmaceutical, paper and paint industries; and
- the available land area, which is influenced by climatic and soil factors.

As illustrated in Figure 3.2, these elements interact with each other within South Africa's social, economic and natural environment, to ultimately influence the availability of maize as feedstock for bioethanol production. Population growth and economic growth are two of the primary driving forces. A driving force is an "…environmental force, driving a possible outcome of a critical uncertainty." (Van der Heijden, 2005:227). Together these driving forces influence the demand for maize as food, animal feed and biomaterials and consequently, total maize demand. Global climate change is the third driving force and influences crop productivity, the land area that is available for the production of maize and consequently, total maize supply.

There are several other elements that also impact on feedstock availability, such as world crop prices and fertiliser availability. Unfortunately, the inclusion of all of these elements would complicate and prolong this investigation. An in-depth economic analysis of global and South African maize demand and supply system is therefore intentionally excluded from this study.

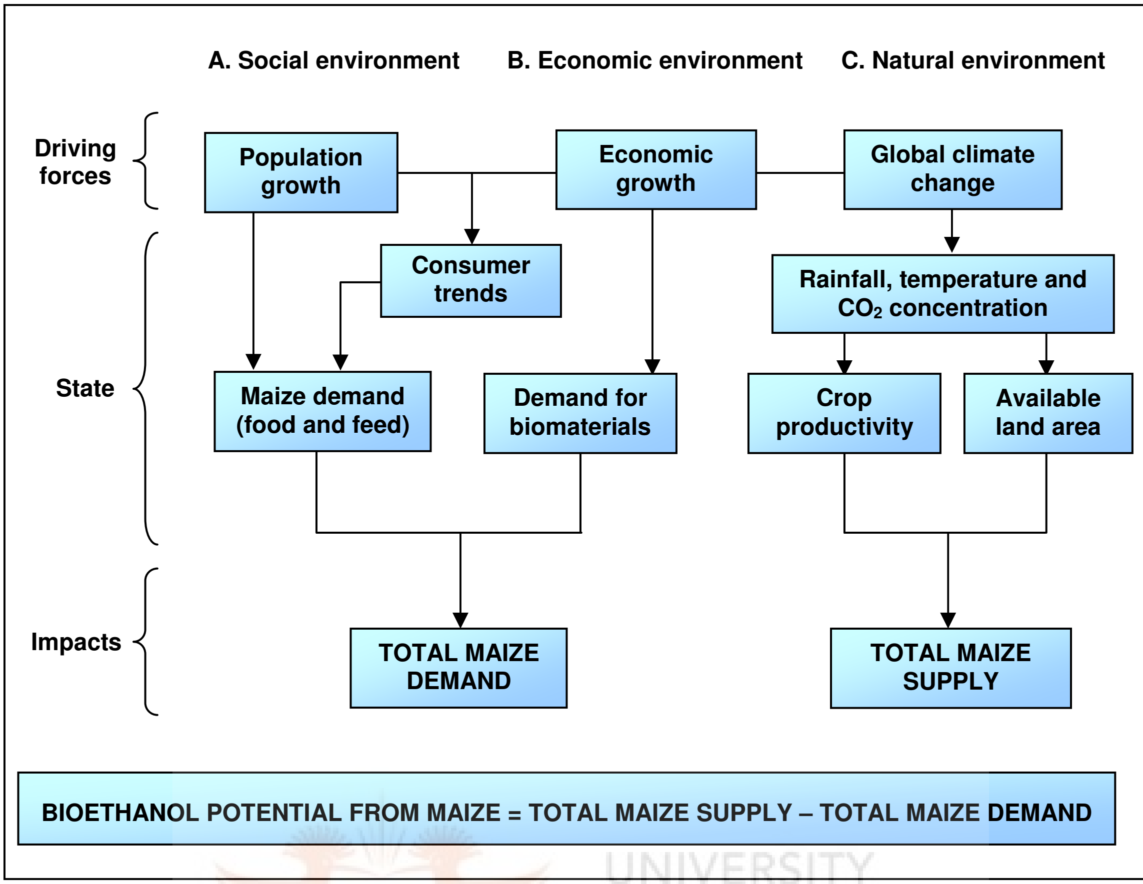

Figure 3.2: Key elements in determining the potential of bioethanol production from maize in South Africa

3.3.1 Maize demand

From a social perspective, maize (*Zea mays L.*) serves as staple food for the majority of the South African population (Du Plessis, 2003:1). For the purpose of this study, maize demand is defined as the amount of maize that is needed to fulfill the national need for human consumption. According to Hoogwijk *et al*. (2005:131) maize demand is primarily influenced by two factors, namely population size and food consumption trends. Secondary factors that influence maize demand include world maize prices and exchange rates (BFAP, 2007a:13), but an in-depth economic analysis is complex and specifically excluded from this study, as discussed in the previous section.

As the size of a population increases, the amount of maize needed to meet domestic demand also increases (BFAP, 2007a:7). To illustrate, the population size and annual maize consumption by humans in South Africa between 1991 and 2006 is shown in Figure 3.3. In spite of some discrepancies (e.g. 1993–1994; 2001–2002; and 2005-2006), both population size and human consumption of maize increased by 31% during this time period. These discrepancies can be attributed to a decrease in the consumer's willingness to buy maize, brought about by the short-term increase in maize prices in response to global shortages of maize supply (NDA, 2006:12).

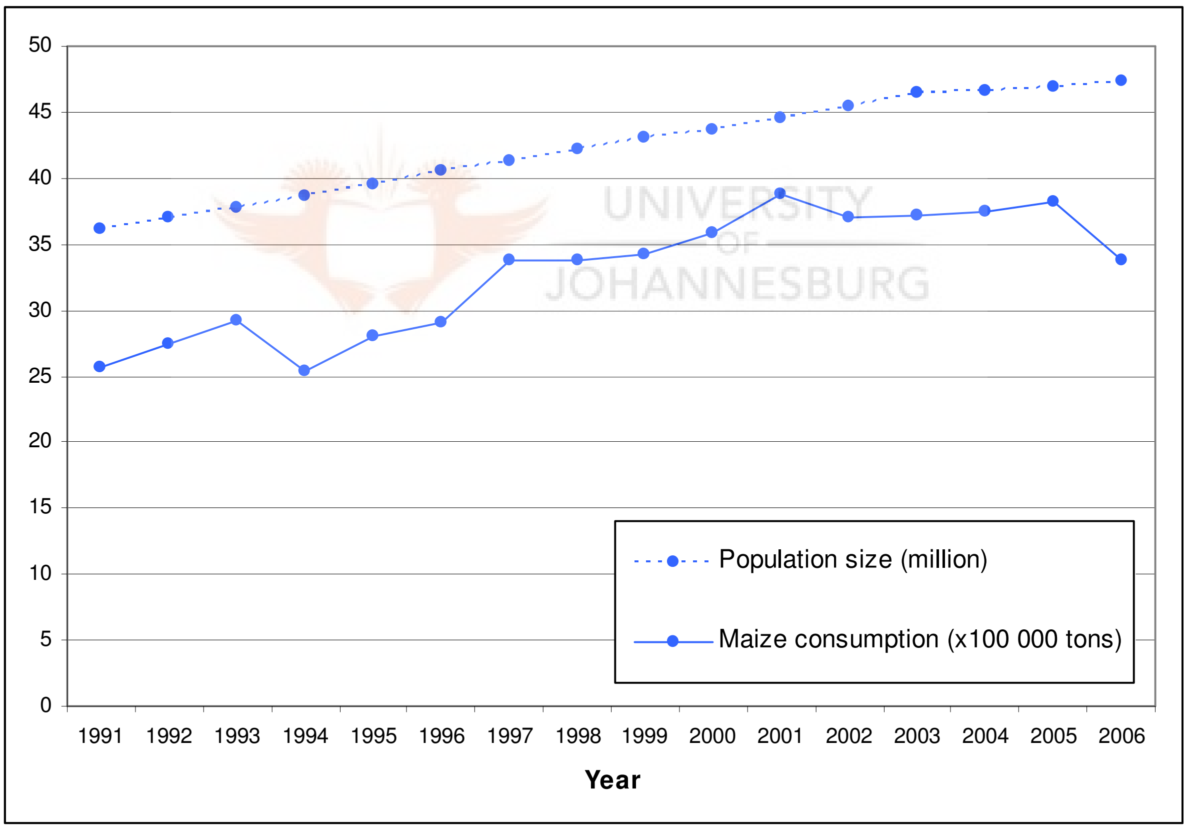

Figure 3.3: Population size and human consumption of maize in South Africa, 1991 – 2006 (Source: DASDA, 2007)

Another factor that influences the demand for maize as food is food consumption trends (Hoogwijk *et al*., 2003:131). Food consumption trends are directly influenced by the economic wealth of a population: wealthy populations have a higher intake of more 'affluent' food types (e.g. meat and dairy products) and a lower intake of basic food types (e.g. maize meal) (Hoogwijk *et al.*, 2005:246). However, no such trend could be observed from an analysis of South African data. As illustrated in Figure 3.4, between 1991 and 2006 the per capita consumption of maize increased from nearly 70 kg to 92 kg per annum (32%). During the same time period the annual consumption of dairy products remained almost constant and the consumption of red and white meat increased by only 8 kg (18% in total).

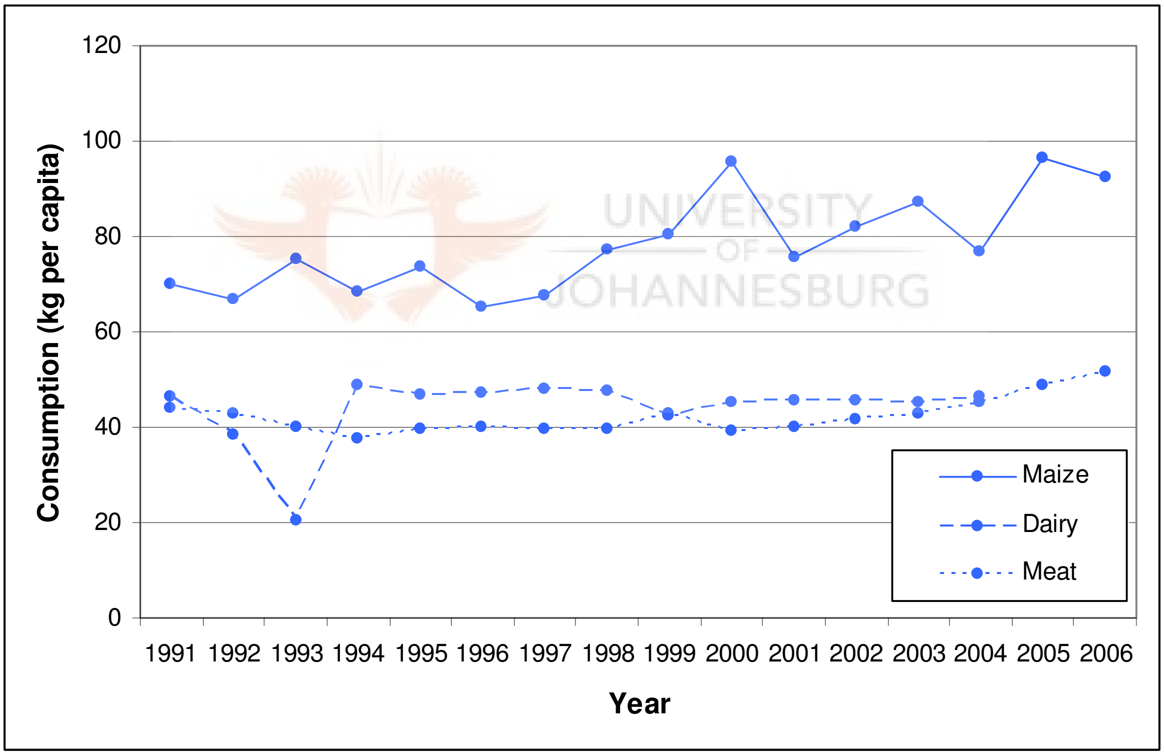

Figure 3.4: Consumption of maize, dairy products and meat in South Africa, 1991 - 2006 (Source: DASDA, 2007)

It is clear that maize consumption increased at a much faster rate than the consumption of the more 'affluent' food types, namely dairy products and meat. In fact, the Bureau for Food and Agricultural Policy (BFAP, 2007a:55) found that even though the real annual per capita income of the

South African population increased from R 15 500 to R 17 329 (nearly 12%) between 2004 and 2007, the portion of the population depending on maize as staple food remained constant (BFAP, 2007a:55). The influence of food consumption trends on maize demand, as specified by Hoogwijk *et al*. (2003:131), does therefore not apply to the current food consumption situation in South Africa. For this reason, food consumption trends were not included as an element affecting maize demand in this analysis.

3.3.2 Maize supply

Maize supply is defined as the total amount of maize that is produced within South Africa each year. This includes maize produced on irrigated and dry land, in both the commercial and developing agricultural sectors. It does not, however, include carry-over stocks from the previous season, or maize imported from other countries.

The annual supply, planted area and yields of maize in South Africa between 1991 and 2005 are shown in Table 3.1. Data for 2006 and 2007 was not available when the analysis was performed. During this time period the area planted with maize decreased by more than 2 million hectares. According to the NDA (2006:10) the decrease was due to an effort to balance maize demand and supply. Nevertheless and despite the decrease in the area planted, the total supply of maize increased from almost 3.3 to 7 million tons per annum. This is a direct result of dramatic increases in maize yields (from 0.785 to 3.413 tons per hectare) during the same time period.

The annual supply of maize is therefore influenced by two main factors, namely the available area and the productivity of the crop, or maize yield (Hoogwijk *et al*., 2005:131). In turn, maize yields are highly dependent on environmental variables, such as rainfall, temperature, atmospheric CO_2 concentration and soil properties (Du Plessis, 2003:1).

Table 3.1: Production, planted area and yields of maize in South Africa, 1991 – 2005 (Source: DASDA, 2007)

Year	Area planted with maize (x 1000 ha)	Supply of maize (x 1000 tons)	Maize yield (tons/ha)
1991	4 173	3 277	0.785
1992	4 377	9 997	2.284
1993	4 661	13 275	2.848
1994	3 526	4 866	1.380
1995	3 761	10 171	2.704
1996	4 023	10 136	2.520
1997	3 560	7 693	2.161
1998	3 567	7 946	2.228
1999	4 013	11 455	2.854
2000	3 189	7 772	2.437
2001	3 533	10 076	2.852
2002	3 651	9 705	2.658
2003	3 204	9 737	3.039
2004	3 223	11 749	3.645
2005	2 032	6 935	3.413

South Africa's agricultural environment is characterised by a high degree of variability in intra-seasonal and inter-annual rainfall and this has a dramatic effect on maize yield (Du Toit *et al*., 2000:2; Martin *et al*., 2000:1473). This effect is enhanced by global climate change and associated global warming (Schulze *et al*., 1993). A study by Du Toit *et al*. (2000:1) showed that global climate change could worsen climatic extremes and cause maize yields in South Africa to decrease by between 10 and 20%.

The use of genetically modified (GM) maize can lead to an increase in maize yields by enhancing the maize plant's growth and natural resistance to pests and climatic extremes (Gouse *et al*., 2005:85). During the past few years genetically modified maize was planted on approximately 29 to 30% of the total area planted with maize (NDA, 2006:10). However, this study does not consider genetically modified maize as a significant factor influencing maize supply, as will be discussed in more detail in Section 3.5.4.

3.3.3 Demand for biomaterials

For the purpose of this study, biomaterials are defined as ‘raw’ maize to be converted to other products, such as foodstuffs, feed and chemicals. In South Africa maize is not only consumed directly by people, but is used as biomaterial in the food, animal feed, textile, pharmaceutical, paper and paint industries (NDA, 2006:9). The demand for biomaterial is defined as the total amount of maize that is not directly consumed by humans each year. This includes the use of maize to produce biomaterials such as animal feed, maize starch, liquid glucose, dextrose monohydrate (DMH), dextrin and sorbitol.

Animal feed is the most important biomaterial derived from maize in South Africa. In fact, approximately 40% of the total annual amount of maize produced in South Africa is used as animal feed in the meat, dairy and poultry industry (NDA, 2006:12). Maize starch is widely used in the food and textile industries. Liquid glucose is used in the pharmaceutical industry to produce cough syrups and tonics. Similarly, dextrose monohydrate is used to produce penicillin and *Oral Rehydrate Solutions* (ORS) for the treatment of illnesses such as diarrhoea, dehydration and heat stroke. It is further used in the food industry as a yeast substrate and preservative. Dextrin is used as a thickener, dye and binding agent in the textile printing industry and it can be used in the preparation of certain antibiotics. In the paper industry, sorbitol is used to increase the flexibility of paper. Sorbitol can also serve as a cost effective replacement of propylene glycol in paint (GAE, 2007).

The amount of maize consumed as biomaterial in the food, animal feed, textile, pharmaceutical, paper and paint industries in South Africa is illustrated in Figure 3.5.

Several regression analyses were performed to determine whether meat production, egg production and population size specifically influence the demand for maize as biomaterial. However, no meaningful relationships could be established. For the purposes of this study, it is therefore assumed that the demand for maize as biomaterial will remain constant at 3.5 million tons per annum until 2013. This amount equals the average demand for maize as biomaterial between 1991 and 2006 (DASDA, 2007).

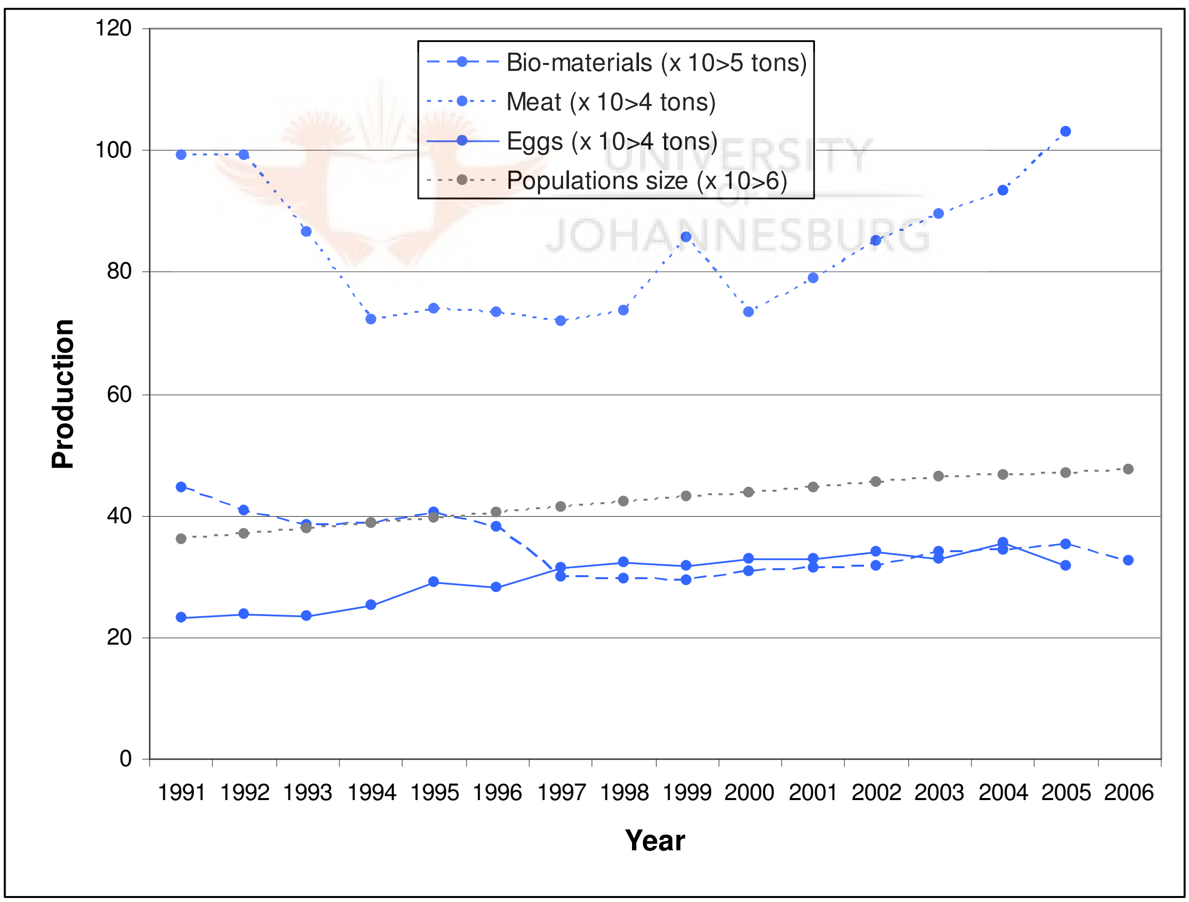

Figure 3.5: Demand for maize as biomaterial, meat and egg production and population size in South Africa, 1991 - 2006 (Source: DASDA, 2007)

3.3.4 Available land area

As noted in Chapter 1, the land area that is available for the production of energy crops is very limited. In South Africa maize production must compete with other land-uses such as grazing, forestry, human settlements, nature conservation and the production of other food crops. The available area is further restricted to specific regions with suitable climatic and soil properties (Walsh *et al.*, 2003:318).

For the purposes of this study, the available land area is defined as the area of land that is not occupied by competing land-uses and is located in regions with suitable climatic and soil properties. Competing land-uses include land used for grazing, forestry, human settlements, mines and quarries. Suitable climatic properties include annual rainfall exceeding 350 mm, mean daily temperatures between 19℃ and 32℃, and mean summer temperatures below 23℃. A frost-free period of more than 140 days per annum is required to grow maize. Suitable soil properties include soil depths exceeding 450 mm, good internal soil drainage, sufficient nutrients and clay contents between 10 and 30% (Du Plessis, 2003:11; Schoeman & Van der Walt, 2006:20).

3.3.5 Availability of maize for bioethanol production

The availability of maize for the production of bioethanol is defined as the difference between total maize supply and total maize demand, and is measured in tons. As stated in Section 3.3.2, the annual supply of maize does not include carry-over stocks from the previous season, or maize imported from other countries, but only the maize produced in South Africa during one season. This study assumes that total maize demand (food and biomaterials) must be met before any remaining maize can be utilised as feedstock for bioethanol production.

The availability of maize for bioethanol production can be converted to a technical potential for bioethanol. The technical potential for bioethanol is defined as the amount of bioethanol, measured in liters, which can be produced from a given amount of maize. The technical potential depends on the conversion efficiency of the conversion technology used. The conversion efficiency used in this study has been established from values published in the literature and will be discussed in Section 3.5.3.

3.4 Modelling bioethanol potential from maize

The information stated in the previous section can be used to develop a model for determining the potential for bioethanol production from maize in South Africa. This model will contain the four key elements identified and defined in the previous section.

3.4.1 Temporal scope

This study focuses on the time period between 2008 and 2013. This will allow comparison with the aims of the *Draft Biofuels Industrial Strategy* (DME, 2006a) which aims to increase the use of biofuels to replace 4.5% of conventional transport fuels by 2013.

The short-term focus adopted in this study allows one to predict the directionality and size of the driving forces which impact on bioethanol production in South Africa (i.e. social, economic and environmental change) more accurately. On the other hand, it minimises the degree of uncertainty inherent in predicting the future, thereby ensuring a higher degree of accuracy in the model outputs. This concept is illustrated in Figure 3.6, which shows the balance of predictability and uncertainty in planning. It can be seen that the longer the focus of the study, the more difficult it becomes to accurately define or predict the driving forces affecting the future environment (Van der Heijden, 2005:97).

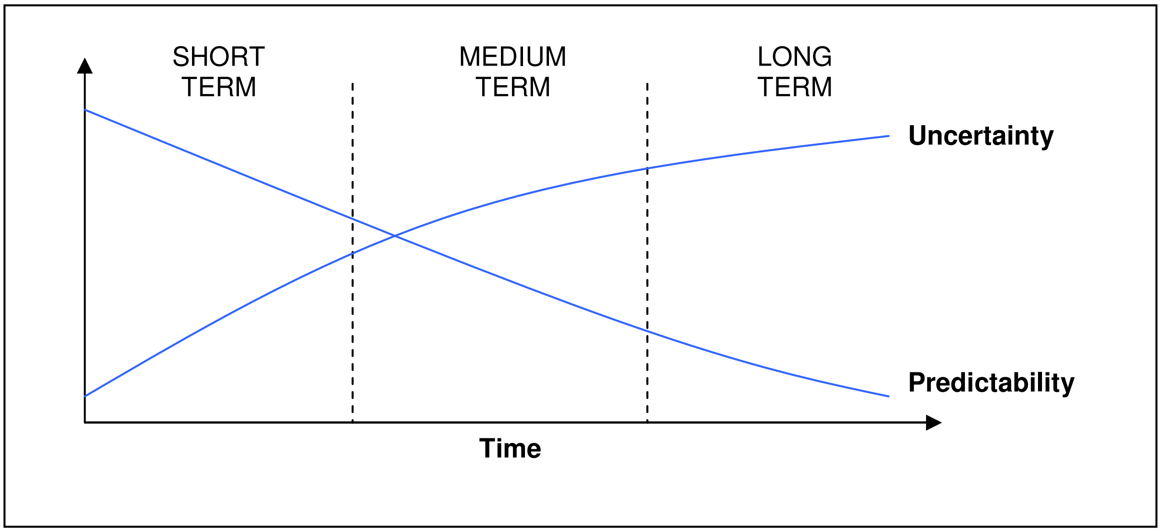

Figure 3.6: The balance of predictability and uncertainty in planning
(Source: Adapted from Van der Heijden, 2005:99)

3.4.2 Description of the model

The model follows a series of four steps which are illustrated in Figure 3.7. Each step utilises data from different sources and involves similar quantitative techniques. Step 1 uses data on the available land area for maize production and future maize yields in order to calculate total maize supply. Future population size and the demand for maize as biomaterial is used to calculate total maize demand. Consequently, the availability of maize for bioethanol production is determined in Step 3 and converted to the technical potential for bioethanol production from maize in Step 4.

3.4.2.1 Calculate total maize supply

As noted in Section 3.3.2, total maize supply is a function of maize yields and the available land area. The total amount of maize that can be produced is the product of the area planted with maize and the amount of maize produced per unit area.

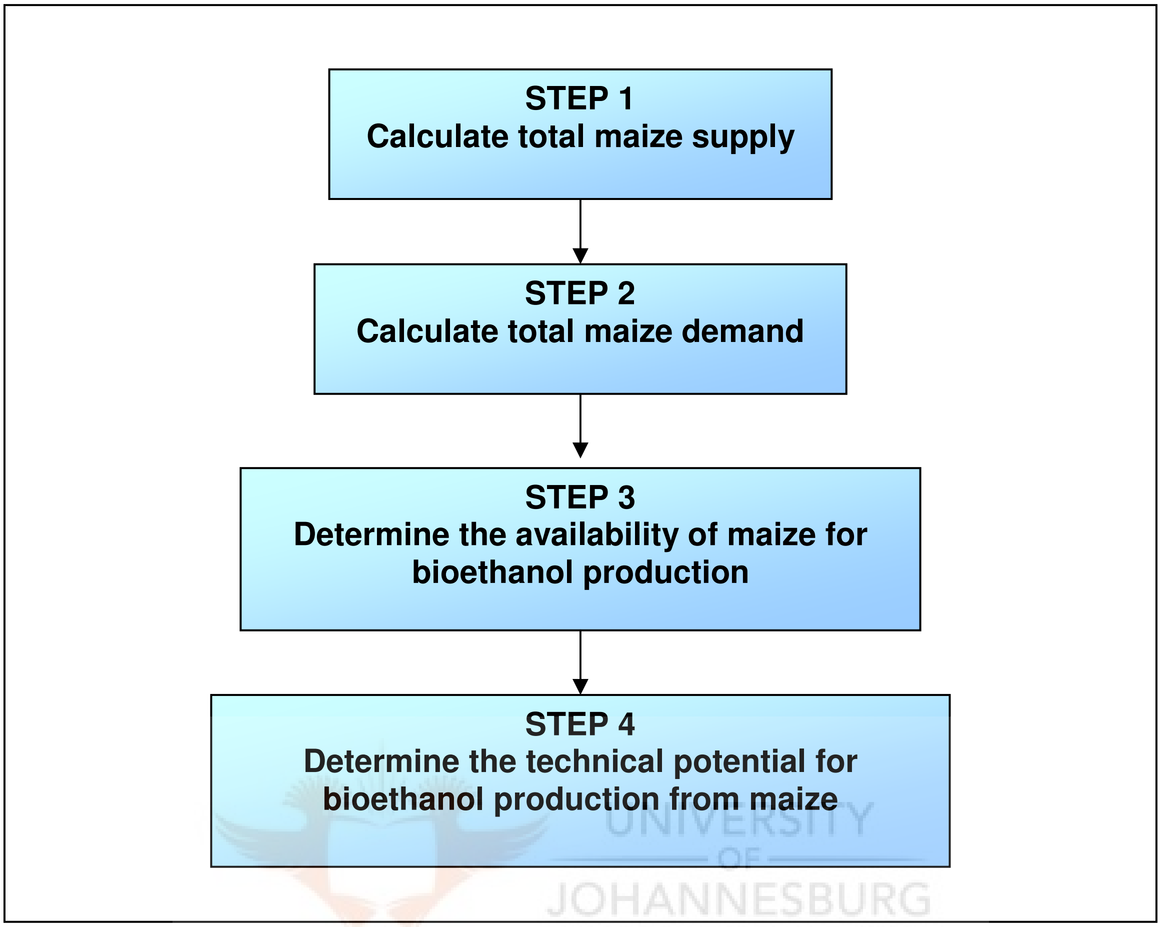

Figure 3.7: Steps of the bioethanol potential model

The total amount of maize supplied during any given time period is therefore defined as:

$$S_{total} = Y \times A_{available} \tag{3.3}$$

Where,

S_{total}	=	total maize supply (kt);
Y	=	maize yield during that time period (kt/ha); and
$A_{available}$	=	the available land area (ha).

Determining the impact of global climate change on maize yields in South Africa is a complex procedure and is beyond the scope of this study. For the purpose of this study, data on future maize yields are therefore derived from other sources, such as the Bureau for Food and Agricultural Policy (BFAP, 2007b). The South African National Climate Change Committee (Du Toit *et al*., 2000) aimed to simulate the possible changes in maize yields due to global climate change using the CERES-Maize computer model (Jones & Kiniry, 1986) calibrated to South African conditions. They obtained results for the future percentage changes in maize yields for nineteen sites in major maize production regions of South Africa. The main environmental variables that were taken into account were rainfall and atmospheric CO_2 concentrations. Changes in maize yields for the nineteen sites in question were extrapolated to national levels by the Bureau for Food and Agricultural Policy (BFAP, 2007b). For the purpose of this study, it is assumed that climate change could result in a 5 to 10% decrease in rainfall over the South African interior and that future increases in atmospheric CO_2 concentrations would result in improved maize growth (BFAP, 2007b:29). Current maize yields are derived from the Crop Estimates Committee (CEC, 2007).

On the other hand, data on the land area that is available for maize production in South Africa are derived from the South African Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW). Based on climatic and soil data, the ARC-ISCW (Schoeman & Van der Walt, 2006) distinguishes five different land suitability categories for maize production, as illustrated in Figure 3.8. This includes highly suitable land, with little or no limitations; suitable land, with slight limitations; moderately suitable land, with moderate limitations; and marginal land, with severe limitations. The fifth category, non-suitable land, includes land occupied by competing land-uses, such as land for grazing, forestry, nature conservation, urban settlements, mines and quarries.

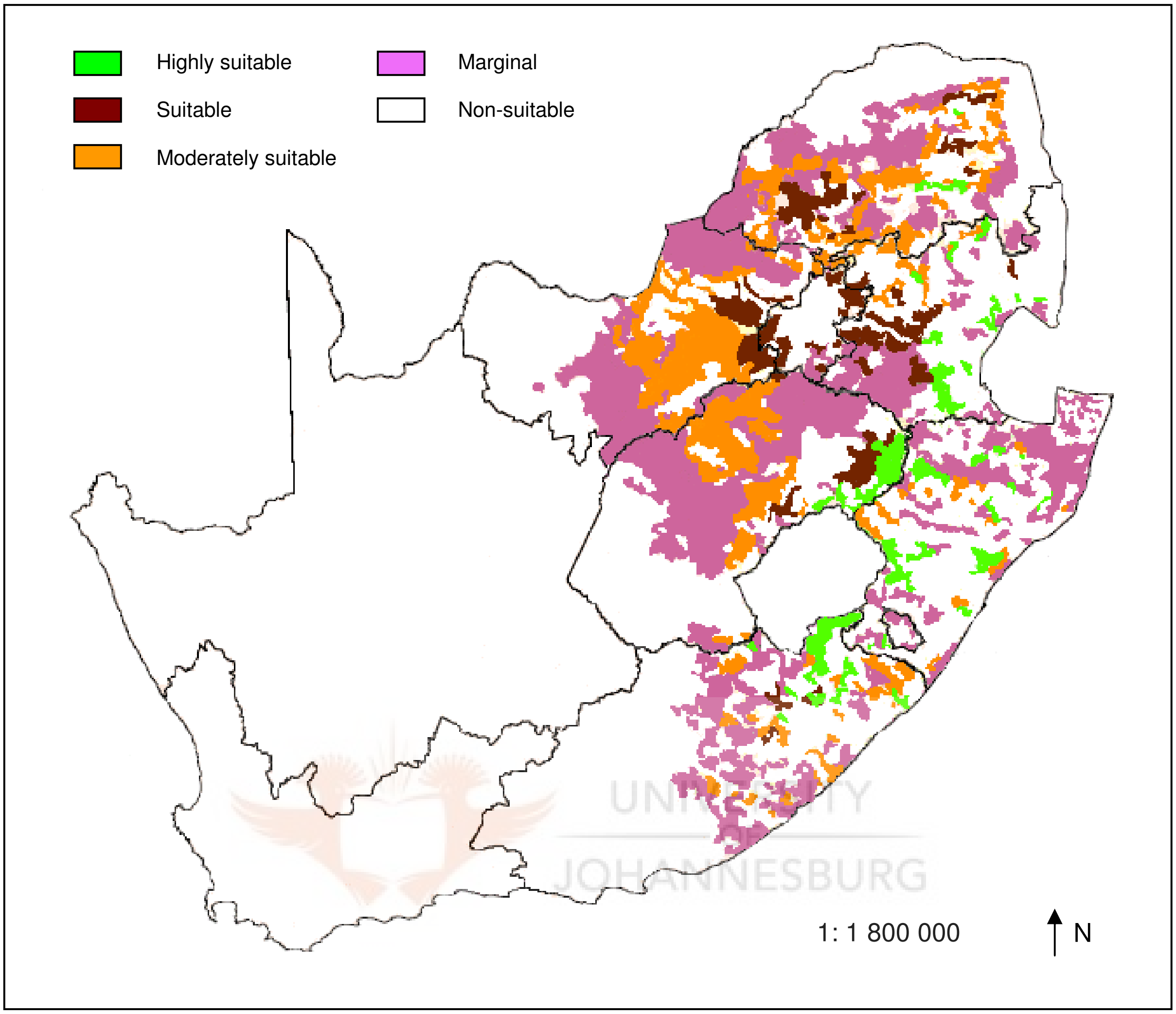

Figure 3.8: Land suitability categories for maize production in South Africa (Source: Adapted from Schoeman & Van der Walt, 2006:13)

The four land suitability categories for maize production, as classified by Schoeman and Van der Walt (2006), are summarised in Table 3.2. According to this table, only 1.5 million hectares of land is classified as highly suitable in South Africa. On the other hand, a massive 9.2 million hectares of land is classified as marginal land. The soil and climatic properties of these four land suitability categories are summarised in Schoeman and Van der Walt (2006:20). It is important to mention that in the past, the cultivation of marginal land in South Africa has led to land degradation (De Villiers *et al.*, 2003:45; Meadows & Hoffman, 2003:170). In turn, land degradation has led to an increase in South Africa's vulnerability to droughts and consequently, food insecurity (NDA, 2005:5). Therefore, this study assumes that marginal land is not utilised for maize production. Only suitable, highly suitable and moderately suitable land is planted with maize.

Table 3.2: Areas of land suitability classes in South Africa (Source: Derived from Schoeman & Van der Walt, 2006:13 and NDA, 2006:10)

Maize type	Highly suitable land	Suitable land	Moderately suitable land	Marginal land
	ha			
White maize[1]	1 007 500	2 028 000	4 516 850	5 985 850
Yellow maize[2]	542 500	1 092 000	2 432 150	3 223 150
TOTAL	1 550 000	3 120 000	6 949 000	9 209 000

Notes: [1] 65% of the total land area
[2] 35% of the total land area

3.4.2.2 Calculate total maize demand

Total maize demand (D_{total}) includes the amount of maize needed to fulfill domestic demands for food and biomaterials.

Total maize demand during a given period is defined as:

$$D_{total} = D_{food} + D_{bio} \tag{3.4}$$

Where,

D_{total} = total maize demand (kt);

D_{food} = maize demand for food (kt); and

D_{bio} = demand for maize as biomaterial (kt).

As stated in Section 3.3.1, the demand for maize as food depends on population size. Future population sizes for each year up to 2013 are based on different sources, such as Statistics South Africa (StatsSA, 2007:3) and the Bureau of Market Research (Van Aardt, 2007) at the University of South Africa. The quantitative relationship between maize demand for food (D_{food}) and population size (P) in South Africa, for the period between 1991 and 2006, was derived from the *Abstract of Agricultural Statistics* (DASDA, 2007).

Figure 3.9 shows that as population size in South Africa increases, the annual amount of maize consumed as food also increases. This study uses the expected values of maize demand, shown as the solid line in Figure 3.9, to further project the future demand for maize as food in South Africa.

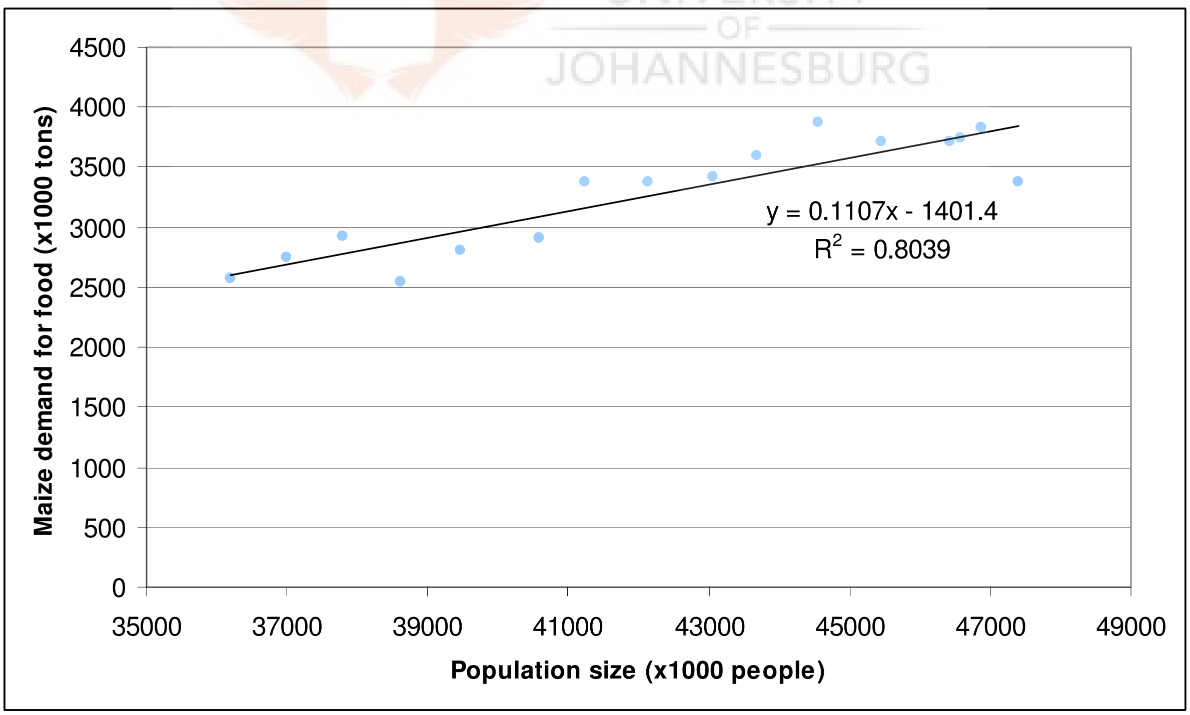

Figure 3.9: Relationship between population size and maize demand for food, 1991 - 2006

Consequently, maize demand for food (D_{food}), measured in tons of maize, is explained by the linear equation:

$$D_{food} = 0.1107(P) - 1400$$

(3.5)

Where,

D_{food} = maize demand for food (kt);

P = population size (thousand); and

R^2 = 0.8039.

In Section 3.3.3 it was explained that it has been assumed that maize demand for biomaterials will remain 3.5 million tons per annum until 2013.

Therefore, based on equations (3.4) and (3.5) total maize demand can be defined as:

$$D_{total} = [0.1107(P) - 1400] + [3500]$$

$$= 0.1107(P) + 4900$$

(3.6)

Where,

D_{total} = total maize demand (kt);

P = population size (thousand); and

D_{food} = demand for maize as food (kt).

3.4.2.3 Determine the availability of maize for bioethanol production

Determining the availability of maize for bioethanol production in South Africa cannot be separated from the previous three steps. In Section 3.3.5, the availability of maize for bioethanol production was defined as the difference between total maize supply and total maize demand. Therefore, the availability of maize for bioethanol production, measured in tons of maize, is defined as:

$$Availability = S_{total} - D_{total}$$

(3.7)

Where,

Availability	=	availability of maize for bioethanol production (kt);
S_{total}	=	total maize supply (kt); and
D_{total}	=	total maize demand (kt).

Based on equations (3.3), (3.6) and (3.7), the availability of maize for bioethanol production can also be defined as:

$$Availability = [Y \times A_{available}] - [0.1107(P) + 4900]$$

(3.8)

Where,

Availability	=	availability of maize for bioethanol production (kt);
Y	=	maize yield (kt/ha);
$A_{available}$	=	available area (ha); and
P	=	population size (thousand).

3.4.2.4 Determine the technical potential of bioethanol from maize

The availability of maize for bioethanol production, measured in tons of maize, is multiplied by a conversion efficiency (η) to determine the technical potential for bioethanol from maize, measured in liters.

Therefore, the technical potential is defined as:

$$Potential = Availability \times \eta \tag{3.9}$$

Where,

Potential	=	Technical potential of bioethanol from maize (kl);
Availability	=	Availability of maize for bioethanol production (kt); and
η	=	conversion efficiency (l/t).

3.4.3 Sensitivity analysis

A sensitivity analysis is included to determine which of the three input factors (i.e. maize yield, available area and population size) contribute most to variability in the model outputs. If a small change in one input factor results in a relatively large change in the model outputs, the outputs are said to be sensitive to that particular input factor. The details of the sensitivity analysis are discussed in Section 4.7.

3.5 Main assumptions

There are four main assumptions in this study, besides the assumptions made during the development of the bioethanol potential model. These assumptions are made in order to reduce the complexity of the model:

1. Food security must be achieved before a large-scale bioethanol programme can be launched. In other words, only maize surpluses are to be used for bioethanol production;

2. Maize exports should be restricted and used for domestic purposes, whether for food and animal feed, or for the production of bioethanol;

3. The conversion efficiency (η) used to determine the potential for bioethanol production in South Africa equals 421 liters of bioethanol per ton of maize; and

4. Improvements in maize production technologies is assumed to have no positive impacts on maize yields in the next five years.

3.5.1 Food security

Food security is defined in the *Integrated Food Security Strategy* (NDA, 2002:15) as the "…physical, social and economic access to sufficient, safe and nutritious food by all South Africans at all times to meet their dietary and food preferences for an active and healthy life." It forms the basis of Section 27 of the *South African Bill of Rights* (1997), where it is stated that everyone has the right to sufficient food and water, and that the government must take legislative and other measures to ensure that these rights are achieved.

In order to achieve food security at a national level the agricultural sector must have the capacity to produce sufficient amounts of food to meet the basic food needs of the population (NDA, 2002:15). If current trends continue, maize consumption could exceed domestic production by 2010 (NDA, 2002:20). In fact, South Africa already has difficulty in producing enough maize to meet domestic demand for food and animal feed (DASDA, 2007:8), mainly due to increased variability in inter-annual rainfall (NDA, 2006:11).

This study assumes that food security must be achieved before a large-scale bioethanol programme can be launched. Therefore, only maize surpluses are available to be utilised for bioethanol production.

3.5.2 International trade

South Africa's international trade in maize consists of exports of white and yellow maize to Botswana, Lesotho, Namibia, Swaziland, Zimbabwe, Angola, Mozambique and Japan, and imports of mainly yellow maize from Argentina (NDA, 2006:13).

The export of maize is a major source of foreign exchange for South Africa (NDA, 2006:12). Since 1999 South Africa has exported an average of 840 750 tons of white maize and 262 500 tons of yellow maize per annum (SAGIS, 2007), earning an average of R 930 million each year (DASDA, 2007:87). However, South Africa spent more than R 455 million per annum on maize imports since 2001 (DASDA, 2007:89). Possible depreciation in the value of the South African rand will lead to an increase in the costs of importing maize in the future (NDA, 2006:13).

Consequently, the South African government feels that biofuel production should not depend on maize imports. Rather, the utilisation of domestically produced maize will provide benefits, such as employment opportunities and economic growth (DME, 2006a:9).

From the above discussion it is clear that South Africa is, in fact, a net exporter of maize. In this study it is assumed that the total amount of maize exported each year is rather to be used domestically, whether for food and animal feed, or for the production of bioethanol.

3.5.3 Conversion efficiencies

The conversion efficiency (η) used to determine the technical potential for bioethanol production is derived from values presented in the literature. The National Department of Agriculture (NDA) states that South Africa's first large-scale bioethanol plant in Bothaville will be able to produce 410 liters of bioethanol per ton of maize (NDA, 2006:10). However, the planners of the bioethanol plant in Bothaville state that 421 liters of bioethanol can be produced per ton of maize (Ethanol Africa, 2007). Other authors such as Graboski (2002:13) and Kim and Dale (2004:363) assume conversion efficiencies of 422 liters and up to 460 liters per ton of maize, respectively. The difference between the quoted efficiencies can be attributed to differences in the type of technology used to produce bioethanol. A conversion efficiency of 421 liters per ton of maize, as quoted by the planners of the bioethanol plant in Bothaville (Ethanol Africa, 2007), is assumed for the purposes of this study.

3.5.4 Improvements in maize production technologies

Improvements in maize production technologies include the introduction of high yielding maize cultivars (genetically modified maize), more efficient application of fertilisers and the use of chemical herbicides. These technologies are known to increase maize yields (Du Toit *et al.*, 2000:2). The annual maize yield in South Africa has more than doubled (from 1.6 to 3.6 tons per hectare) over the past twenty years (DASDA, 2007:7), indicating an improvement in agricultural production technologies (Du Plessis, 2003:11; NDA, 2006:11). Although such improvements have occurred, maize yields have dropped more than 0.9 tons per hectare since 2004 (DASDA, 2007:7; CEC, 2007). This drop can be attributed to climate change, manifested as a general reduction in average annual rainfall over the South African interior (Du Toit *et al.*, 2000:2).

This study assumes that any potential increase in maize yields due to improvements in maize production technologies, including the use of genetically modified maize, are marginilised by the negative impact of climate change on maize yields in South Africa. Future maize yields have been derived from the National Climate Change Committee (Du Toit *et al*. 2000), Bureau for Food and Agricultural Policy (BFAP, 2007b) and the Crop Estimates Committee (CEC, 2007), as discussed in Section 3.3.2.

3.6 Synthesis

This chapter provided a description of the model that was developed in order to determine the potential for bioethanol production from maize in South Africa. This model was based on the methodology used by Hoogwijk *et al*. (2005) and incorporates four interrelated elements, including maize demand, maize supply, the demand for maize as biomaterial and the available land. In the following chapter, data on the social, economic and environmental conditions in South Africa will be used to determine the potential for bioethanol production from maize in South Africa under four different bioethanol potential scenarios.

CHAPTER 4
DATA ANALYSIS AND INTERPRETATION

"The Biofuels Draft Strategy aims to achieve a biofuels average market penetration of 4.5% of liquid road transport fuels (petrol and diesel) by 2013 which will contribute 75% to the national Renewable Energy target." (DME, 2006a:9).

4.1 Introduction

This chapter sets out to determine the availability of maize for the production of bioethanol in South Africa. This will be done through the synthesis of four bioethanol potential scenarios which were specifically designed to provide an all-inclusive view regarding the potential for bioethanol production from maize in South Africa and the implications thereof. To this purpose, each scenario plays out a different storyline for the future social, economic and natural environment that will impact on the availability of maize for bioethanol production. The four scenarios will be simulated within the bioethanol potential model developed for this purpose in Chapter 3. The results of each scenario simulation can then be compared to the DME's biofuel target for 2013, as stated in the *Draft Biofuels Industrial Strategy* (DME, 2006a:9). This will be followed by a sensitivity analysis to determine which of the three model input factors (i.e. maize yield, available area and population size) contribute most to the variability of the results.

4.2 Scenario planning as a tool for predicting the future

In order to determine the potential for bioethanol production in a future South Africa, one needs a tool that is able to incorporate very different views regarding the future. For this purpose, the scenario planning approach was chosen as the tool to 'predict' the future. Schwartz (1996:4) defines scenario planning as "…a tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out." Such an approach differs from traditional forecasting in that it allows one to explore the various uncertainties inherent in the future (Van der Heijden, 2005:49).

4.2.1 Uncertainty and predictability in scenario planning

The most important type of uncertainty in planning for the future is the lack of understanding complexity in the social, economic and natural environment. This uncertainty can be managed by analysing historic data on the different elements in question in order to better anticipate the future. One can also reduce environmental complexity by defining and focusing on those elements that show a high degree of predictability (Van der Heijden, 2005:91). Those elements that can be predicted with relative ease, i.e. maize yields, available land and population growth, form the basis for each scenario in this study. Uncertainty is further reduced by analysing the historic trends of these elements and by adopting a short-term focus to scenario planning, as discussed in Section 3.4.1.

4.2.2 Characteristics of effective scenario planning

According to Van der Heijden (2005: 225), there are five characteristics of effective scenario planning, namely:

- At least two scenarios are needed to reveal the degree of inherent uncertainty in the model simulation. The use of more than four scenarios is proven to be impractical and counterproductive;
- Scenarios must be plausible, conceivable and representative of the current status of knowledge regarding the issue under investigation;
- Scenarios must be internally consistent;

- Scenarios must be relevant to the aim of the investigation;
- Scenarios must generate a new perspective regarding the issues that are investigated.

The scenario planning process of this study aimed to fulfill all the requirements of effective scenario planning, as listed by Van der Heijden (2005). To this purpose, four bioethanol potential scenarios were qualitatively formulated to provide an all-inclusive view regarding the study topic. Historic data was quantitatively analysed to ensure that all of the scenarios are plausible, conceivable and representative. Lastly, internal consistency was guaranteed by making use of the bioethanol potential model developed in Chapter 3 for the simulation of these scenarios.

The four bioethanol potential scenarios will be described in the following section. These descriptions are based on the matrix approach to deductive scenario development.

4.3 Scenario descriptions

The matrix approach consists of identifying two or three key elements which will distinguish the scenarios from each other. The resulting matrix consists of four cells, representing four ‘storylines’ or scenario environments. This method ensures that the four storylines are as unique and different as possible within the limits of plausibility (Van der Heijden, 2005:247).

In this study, maize demand and supply were chosen as the key elements that distinguishes each scenario from each other. Maize demand and supply therefore represent the two main axes of the scenario matrix illustrated in Figure 4.1.

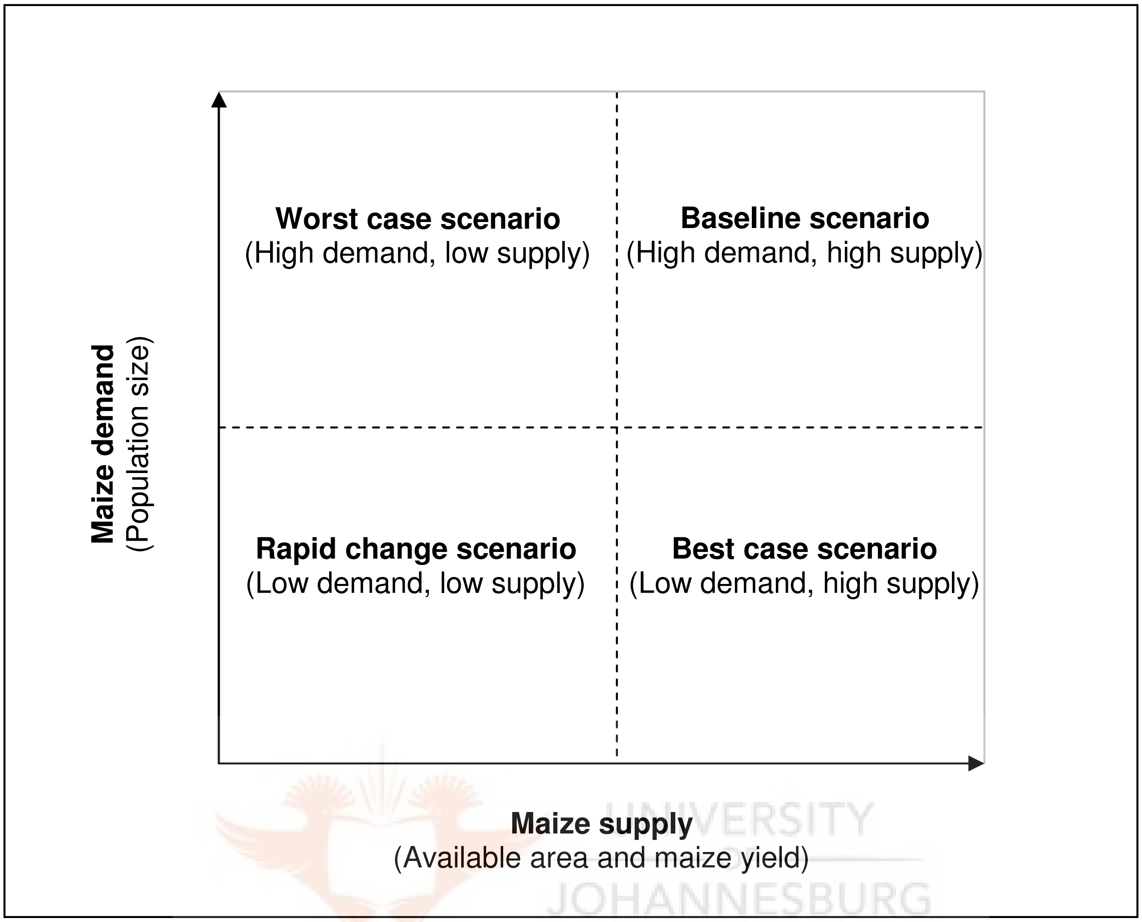

Figure 4.1: Bioethanol potential scenario matrix

The storyline of each scenario is summarised as follows:

- *Baseline scenario*

  Business carries on as usual. South Africa continues to produce increasing amounts of maize to feed the growing population and meet the growing demand for maize.

- *Best case scenario*

  Population growth slows and the demand for maize is less than in the worst case scenario. There are very few constraints on maize production and the supply of maize is more than sufficient to meet local demand.

- *Worst case scenario*

  Population growth continues at the current rate, resulting in an increase in the demand for maize. Maize supply does not, however, increase at the same rate. The negative effects of climate change place constraints on maize production and it becomes increasingly difficult to meet the growing demand for maize.

- *Rapid change scenario*

  The HIV/Aids pandemic is manifested through rapid demographical changes, of which an increase in mortality rates and a decrease in the population growth rate is the most prominent. Rapid global climate change further results in a dramatic decrease in maize yields and the supply of maize.

In the following section each of these four scenarios will be quantitatively analysed and defined, and a quantitative assessment conducted.

4.3.1 Baseline scenario

The baseline scenario was developed as a reference scenario to which the results of the other three scenarios could be compared. The storyline was formulated to reproduce a future social, economic and natural environment similar to that of today. In this scenario, both the demand and supply of maize are relatively high.

In this scenario, global climate change does not result in a decrease in the annual amount of rainfall over the South African interior and therefore, does not impact negatively on the total area that is available for the production of maize, or on maize yields. The suitability and availability of land for maize production also remains constant at current levels. It was assumed that current levels would equal the long-term average of the total land area planted with maize. For this purpose, the average annual land area planted with maize between 1991 and 2006 was calculated. The historic values were given in Table 3.1 and the average was calculated as 3.6 million hectares per annum.

It is unrealistic to assume that maize yields will not increase in this scenario. Improvements in agricultural technology, of which the increased use of genetically modified maize is the most prominent, will ensure an increase in maize yields (see Section 3.5.4). However, no information exists on how to quantitatively determine the extent of future use of genetically modified maize in South Africa, or what the impacts on yields will be. For the purposes of simplification in forecasting, it was therefore assumed that maize yields would increase at an average rate of 0.12 and 0.13 tons per hectare per annum for white and yellow maize, respectively. These rates were calculated from historic data on maize yields in South Africa, shown in Table 3.1.

According to Statistics South Africa (2007), the South African population reached 47.85 million people in mid-2007, increasing at an average growth rate of 1.14% per annum. In the baseline scenario, it is assumed that the South African population would continue to increase by 1.14% per annum until 2013. A summary of the baseline scenario assumptions is provided in Table 4.1.

Table 4.1: Baseline scenario assumptions

Factor	Assumption	Value	Source
Available area	Remains constant	3.6 million ha[1]	DASDA, 2007
Maize yield	Increases at rate equaling the 15-year average	0.12 t/ha p/a for white maize	DASDA, 2007
		0.13 t/ha p/a for yellow maize	
Population size	Increases at the current rate	1.14% p/a	StatsSA, 2007
Notes: [1] White and yellow maize planted on 65% and 35% respectively.			

4.3.2 Best case scenario

The best case scenario was formulated in order to give an optimistic perspective on the availability of maize for the production of bioethanol in South Africa. In the scenario matrix given in Figure 4.1, the best case scenario is characterised by a low demand and high supply of maize. In this scenario, maize supply increases to a hypothetical maximum by 2013. However, it is unrealistic to assume that the demand for maize would not increase correspondingly and therefore, a realistic assumption will be that the demand for maize would increase at current rates.

In the best case scenario, maize supply increases to a hypothetical maximum by 2013. As discussed in Section 3.4.2.1, the use of moderately suitable and marginal land leads to land degradation. For this purpose, only highly suitable and suitable land, as defined by Schoeman and Van der Walt (2006) and described in Section 3.4.2.1, is included in the total land area available for the production of maize. The total land area thus amounts to 4.67 million hectares, as illustrated in Figure 4.2. This is only 1 million hectares more than the historic 15-year average of the land area planted with maize in South Africa. In fact, between 1970 and 1985 an annual average of 4.68 million hectares was planted with maize. The total land area planted with maize in this scenario (i.e. 4.67 million hectares) thus seems realistic and plausible.

Maize supply is also increased to a hypothetical maximum due to an increase in maize yields. However, there is no way of predicting the future increases in maize yields brought about by the use of genetically modified maize and other improvements in agricultural technology. Therefore, the historic increase in maize yields in South Africa (i.e. 0.12 tons/ha/year for white maize and 0.13 tons/ha/year for yellow maize), as described in the baseline scenario, is assumed in this scenario.

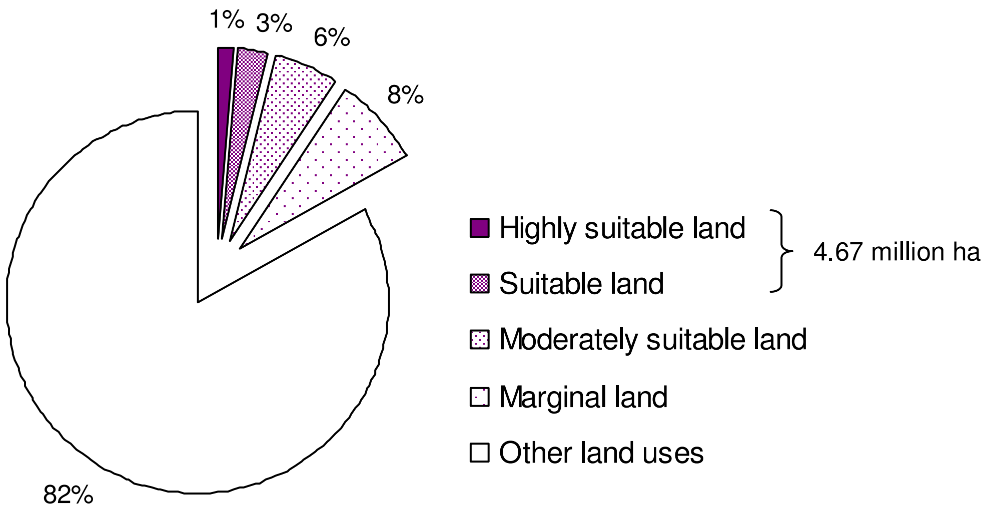

Figure 4.2: Land suitability classes (Source: Schoeman & Van der Walt, 2006)

With respect to population size and maize demand, the population growth rate remains constant at present levels (i.e. 1.14% per annum) in this scenario, as discussed in the baseline scenario. If the rates of increase in maize demand and supply in this scenario are compared to that of the baseline scenario, it can be observed that the demand for maize increases at a slower rate than the supply of maize. A summary of the best case scenario assumptions is provided in Table 4.2.

Table 4.2: Best case scenario assumptions

Factor	Assumption	Value	Source
Available area	Includes only highly suitable and suitable land	4.67 million ha[1]	Schoeman & Van der Walt, 2006
Maize yield	Increases at rate equaling the 15-year average	0.12 t/ha p/a for white maize	DASDA, 2007
		0.13 t/ha p/a for yellow maize	
Population size	Increases at the current rate	1.14% p/a	DASDA, 2007

Notes: [1] White and yellow maize planted on 65% and 35% of the total area, respectively.

4.3.3 Worst case scenario

The worst case scenario was formulated in order to give a pessimistic perspective on the availability of maize for the production of bioethanol in South Africa. In this scenario it becomes more and more difficult to fulfill the increasing demand for maize as food, because of population growth. The worst case scenario is characterised by a high demand for, and low supply of, maize.

In this scenario global climate change results in a decrease in rainfall over the South African interior, causing white and yellow maize yields to decrease by 5.7% and 3.4% per annum, respectively. These rates were predicted in a study by the Bureau for Food and Agricultural Policy (BFAP, 2007b), as discussed in Chapter 3. Climate change would cause white maize yields to decrease at a faster rate, due to a 5 to 10% decrease in annual rainfall over the western maize regions of South Africa, where white maize production dominates (BFAP, 2007b:27). These climatic changes would increase the sensitivity of agricultural land-use systems and the potential threat of land degradation. The land area for maize production will therefore need to be restricted to highly suitable and suitable land, thereby decreasing the risk of land degradation. Taking these factors into account, only 4.67 million hectares would be available for the cultivation of maize.

The South African population is further expected to increase up to 2013. For the purposes of this scenario, it is assumed that the population will grow at a rate of 1.14% per annum. This rate equals the current population growth rate, as discussed in the baseline scenario. A summary of the worst case scenario assumptions is given in Table 4.3.

Table 4.3: Worst case scenario assumptions

Factor	Assumption	Value	Source
Available area	Includes only suitable and highly suitable land	4.67 million ha[1]	Schoeman & Van der Walt, 2006
Maize yield	Decreases due to global climate change	White maize yields decrease 5.7% p/a	BFAP, 2007b
		Yellow maize yields decrease 3.4% p/a	
Population size	Increases at the current rate	1.14% p/a	DASDA, 2007
Notes: [1] White and yellow maize planted on 65% and 35% of the total area, respectively.			

4.3.4 Rapid change scenario

The rapid change scenario was specifically designed to project the impacts of the HIV/Aids pandemic and rapid global climate change on the potential for bioethanol production from maize in South Africa. In this scenario, the South African population growth rate decreases due to the impact of HIV/Aids, of which an increase in mortalities is the most prominent. While HIV/Aids impacts on the population size, rapid global climate change worsens climatic extremes and decreases the amount of rainfall over the South African interior, thereby dramatically decreasing maize yields. The rapid change scenario is characterised by a low demand and low supply of maize.

In this scenario, the land area that is available for the production of maize is restricted to highly suitable and suitable land, thus decreasing the risk of land degradation. Therefore, only 4.67 million hectares are available for the cultivation of maize. Rapid global climate change is further expected to result in decreases in white and yellow maize yields of 5.6% and 4.5% per annum, respectively. The decrease in maize yields is more than assumed in the worst case scenario, due to the absence of the 'fertilisation effect' (BFAP, 2007b:29). In other words, increased atmospheric concentrations of CO_2 prove to have no positive effect on maize growth and consequently, maize yields decrease.

The impact of HIV/Aids would result in rapid demographical changes in South Africa. The average population growth rate between 1991 and 2006 is expected to decrease from 1.14% per annum to only 0.4% per annum by 2013. These projections are based on a study by Dorrington *et al.* (2006) from the Centre for Actuarial Research. Their study aimed to determine the demographical changes resulting from HIV/Aids in South Africa to 2015. A summary of the rapid change scenario assumptions is given in Table 4.4.

Table 4.4: Rapid change scenario assumptions

Factor	Assumption	Value	Source
Available area	Includes only suitable and highly suitable land	4.67 million ha[1]	Schoeman & Van der Walt, 2006
Maize yield	Decreases due to global climate change (fertilisation effect absent)	White maize yields decrease 5.6% p/a	BFAP, 2007b
		Yellow maize yields decrease 4.5% p/a	
Population size	Decreases due to HIV/Aids	0.4% p/a by 2013	Dorrington *et al.*, 2006
Notes: [1] White and yellow maize planted on 65% and 35% of the total area, respectively.			

4.4 Data analysis and interpretation

Data analysis and interpretation of each bioethanol potential scenario is done according to the four steps of the bioethanol potential model described in Chapter 3. The detailed results are provided in Appendix A.

4.4.1 Baseline scenario simulation and results

The quantitative assumptions for the baseline scenario as tabulated in Table 4.1 were used as inputs into the bioethanol potential model. The results are summarised in and presented in Figure 4.3.

The availability of maize for the production of bioethanol was calculated as 4.6 million tons in 2013. The availability increases by more than 1.9 million tons between 2008 and 2013 under the circumstances sketched in this scenario. The amount of available maize could be used to produce approximately 1.9 billion liters of bioethanol by 2013.

Table 4.5: Summary of the baseline scenario results

Year	Maize demand	Maize supply	Availability of maize for bioethanol production	Bioethanol potential*
	million tons			million liters
2008	7.457	10.159	2.702	1 137
2009	7.518	10.604	3.086	1 299
2010	7.580	11.049	3.468	1 460
2011	7.643	11.493	3.850	1 621
2012	7.706	11.938	4.232	1 781
2013	7.770	12.382	4.613	1 941

Note: * Calculated at 421 litres of bioethanol per ton of maize

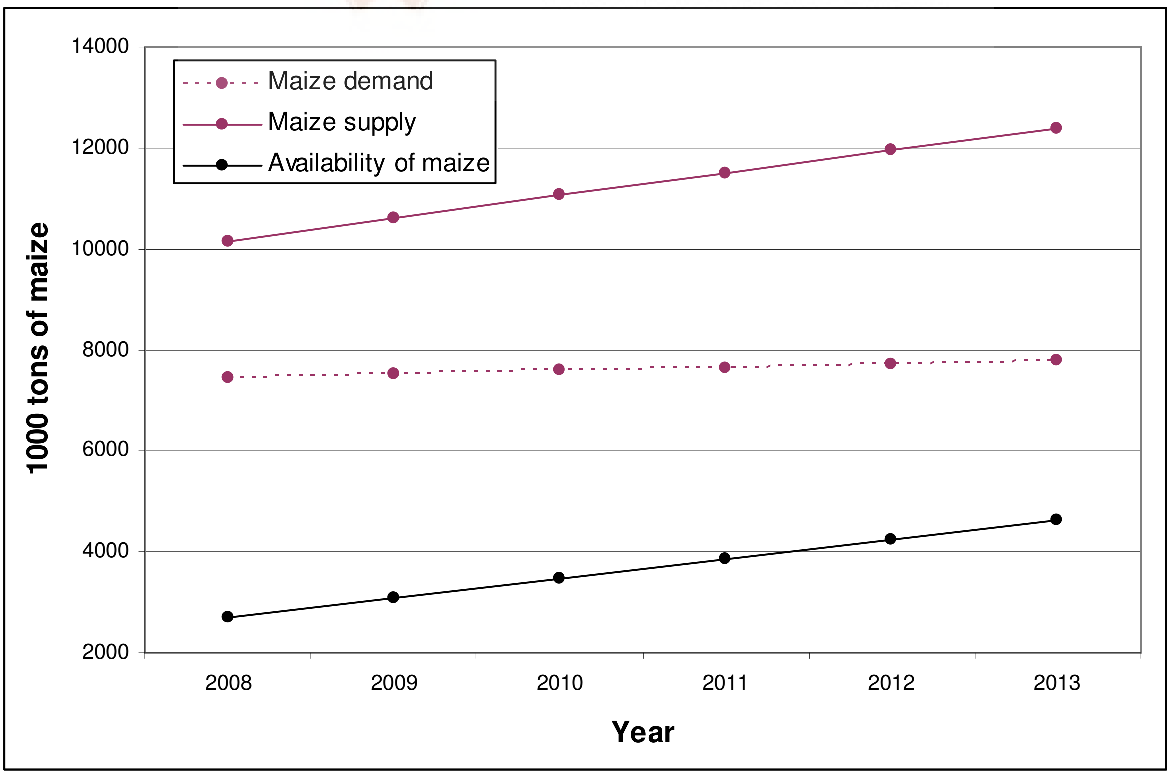

Figure 4.3: Baseline scenario results

Each assumption of the baseline scenario was quantitatively determined from historic data on maize production in South Africa. If and only if the current trends in South Africa's agricultural sector remain constant, will this scenario prove to be true. In this case it seems entirely plausible to produce enough maize to produce 1.9 billion liters of bioethanol by 2013.

4.4.2 Best case scenario simulation and results

The quantitative assumptions for the best case scenario as tabulated in Table 4.2 were used as inputs into the bioethanol potential model. The results are summarised in Table 4.6 and presented in Figure 4.4.

As in the baseline scenario, total maize demand is expected to increase at an average rate of 1.5% per annum and was calculated to equal approximately 7.77 million tons in 2013. However, according to the scenario assumptions total maize supply is projected to increase at a much faster rate.

The planting of 4.67 million hectares of highly suitable and suitable land, as assumed in this scenario, would result in total maize supplies amounting to 16 million tons in 2013. This is approximately 2.7 million tons more than the highest annual supply of maize during the past 15 years. This seems plausible, taking into account an increased amount of land area planted with maize and the probable increase in maize yields brought about by improvements in agricultural technology and the increasing use of genetically modified maize. The total demand for maize would therefore be easily met and more than 8.3 million tons of maize would be available for the production of 3.49 billion liters of bioethanol by 2013.

Table 4.6: Summary of the best case scenario results

Year	Maize demand	Maize supply	Availability of maize for bioethanol production	Bioethanol potential*
	million tons			million liters
2008	7.457	13.179	5.722	2 408
2009	7.518	13.756	6.237	2 626
2010	7.580	14.332	6.752	2 843
2011	7.643	14.909	7.267	3 059
2012	7.706	15.486	7.780	3 275
2013	7.770	16.063	8.293	3 491

Note: * Calculated at 421 litres of bioethanol per ton of maize

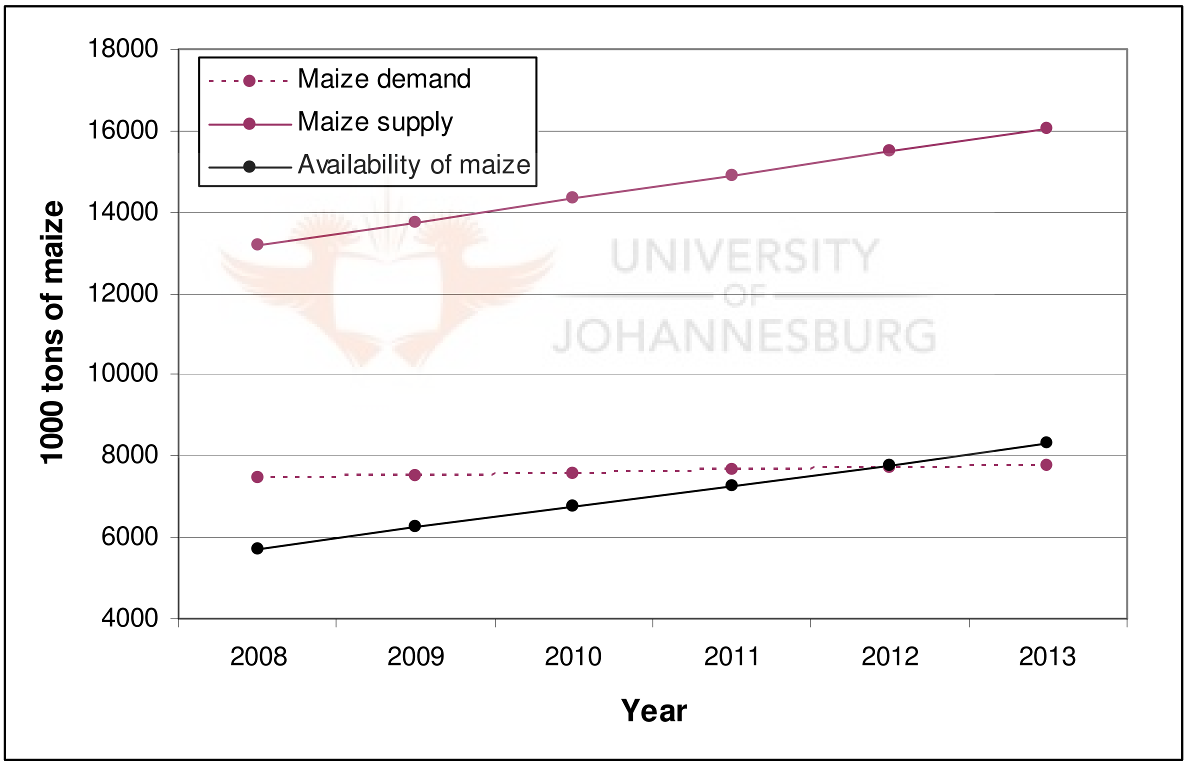

Figure 4.4: Best case scenario results

This scenario does not however take into account the additional resource requirements that will be needed to increase maize production to the assumed level. A large amount of economic resources, such as capital investments in small and large scale agricultural projects will be needed. Human resources would be required, such as skilled agricultural workers.

Other inputs include farming equipment, maize seeds, fertilisers and irrigation equipment. Whether South Africa will be able to supply all of these resources is uncertain and therefore, it is not possible to determine the true feasibility of this scenario. No assessment has been made of the resource requirements and a significant change in policy to support the resource needs of this scenario will be essential.

4.4.3 Worst case scenario simulation and results

The quantitative assumptions for the worst case scenario as tabulated in Table 4.3 were used as inputs into the bioethanol potential model. The results are summarised in Table 4.7 and presented in Figure 4.5.

As assumed in the worst case scenario, global climate change would result in a decrease in rainfall over the South African interior and thereby decrease white and yellow maize yields by approximately 5.7 and 3.4% per annum, respectively (BFAP, 2007b:27). It was calculated that lower yields would cause total maize supply to decrease from 11.9 to 9.4 million tons between 2008 and 2013. This effect, combined with a 0.32 million tons increase in the total demand for maize during the same time period, would result in less maize being available for the production of bioethanol.

Table 4.7: Summary of the worst case scenario results

Year	Maize demand	Maize supply	Availability of maize for bioethanol production	Bioethanol potential*
	million tons			million liters
2008	7.457	11.996	4.539	1 910
2009	7.518	11.421	3.903	1 643
2010	7.580	10.875	3.295	1 387
2011	7.643	10.357	2.714	1 142
2012	7.706	9.864	2.159	908
2013	7.770	9.397	1.627	684

Note: * Calculated at 421 litres of bioethanol per ton of maize

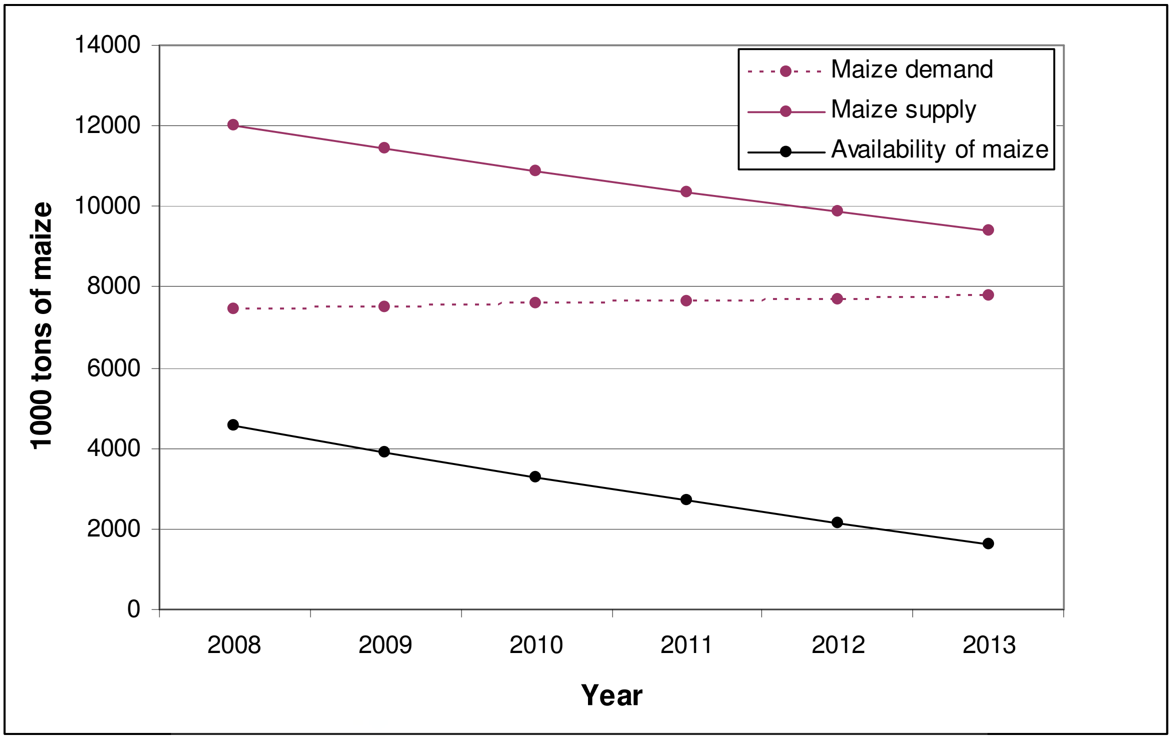

Figure 4.5: Worst case scenario results

The worst case scenario results show that only 1.6 million tons of maize could therefore be used to produce approximately 684 million liters of bioethanol in 2013.

4.4.4 Rapid change scenario simulation and results

The quantitative assumptions for the rapid change scenario as tabulated in Table 4.4 were used as inputs into the bioethanol potential model. The results are summarised in Table 4.8 and presented in Figure 4.6.

Total maize demand was calculated to increase from 7.4 to 7.6 million tons between 2008 and 2013. The total increase in maize demand is approximately 100 000 tons less than in the previous three scenarios and can be attributed to the decrease in the population growth rate caused by HIV/Aids, as assumed to take effect in this scenario.

The rapid change scenario was further based on the assumption that white and yellow maize yields would decrease at a rate of 5.6% and 4.5% per annum, respectively (BFAP, 2007b:28). Total maize supply was therefore calculated to decrease dramatically, amounting to only 9.6 million tons in 2013. The possibility exists that an increase in mortalities due to HIV/Aids could result in a shortage of skilled farm labourers. This could hamper South Africa's ability to produce maize, thereby further reducing potential maize supplies. However, no quantitative data exists on the possible impact of HIV/Aids on South Africa's agricultural labour sector. This aspect could therefore not be quantitatively incorporated into this scenario.

The decreasing demand and supply of maize result in only 1.964 million tons of maize being available for the production of bioethanol by 2013. At a conversion rate of 421 liters/ton of maize, South Africa will be able to produce only 827 million liters of bioethanol by 2013 under the conditions sketched in this scenario. This is 140 million liters more than projected in the worst case scenario and can be ascribed to the lower demand for maize in the rapid change scenario, due to the negative impact of HIV/Aids on the population growth rate.

Table 4.8: Summary of the rapid change scenario results

Year	Maize demand	Maize supply	Availability of maize for bioethanol production	Bioethanol potential*
	million tons			million liters
2008	7.474	12.5	5.026	2 116
2009	7.508	11.9	4.345	1 829
2010	7.541	11.2	3.700	1 558
2011	7.571	10.7	3.090	1 301
2012	7.598	10.1	2.512	1 057
2013	7.624	9.6	1.964	827

Note: * Calculated at 421 litres of bioethanol per ton of maize

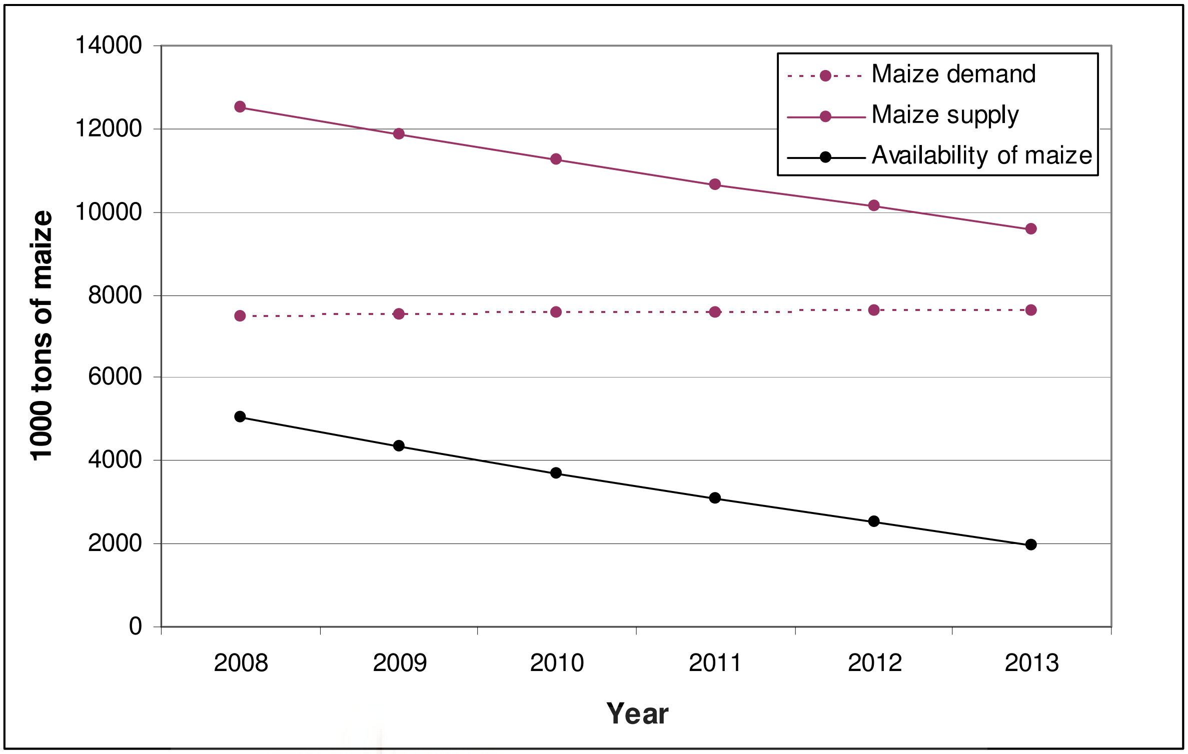

Figure 4.6: Rapid change scenario results

4.5 Biofuel production goals and scenario results compared

The DME set the goal to achieve an average biofuel market penetration, bioethanol and biodiesel included, equaling 4.5% of liquid road transport fuels by 2013 (DME, 2006a:9). The specific target for bioethanol is to supply 80% of South Africa's road transport fuels, in the form of E10, a blend of 10% bioethanol and 90% petrol. The remaining 20% was to be supplied in the form of biodiesel (DME, 2006a:10).

In 2006 approximately 11.28 billion liters of petrol was used as road transport fuel in South Africa (SAPIA, 2007). If one assumes a probable product-demand growth rate equaling the current growth rate of 1% per annum (SAPIA, 2007), the demand for petrol as road transport fuel will increase to 12.09 billion liters per annum by 2013[3]. For the DME's biofuel target to be realised, this would require the production of 1.209 billion liters of bioethanol per annum by 2013.

Towards the end of this study, the DME released their final *Biofuels Industrial Strategy* (2007) with the aim to increase the use of biofuels to replace 2% of conventional transport fuels by 2013. This is 2.5% less than that aimed for in the *Draft Biofuels Industrial Strategy* (2006a). South Africa would therefore only have to produce 537 million liters of bioethanol per annum by 2013. However, for the purposes of this study, reference will be made to the DME's biofuel target as stated in the *Draft Biofuels Industrial Strategy* (2006a).

Each of the four bioethanol potential scenarios can now be compared with the biofuel target stated by the DME in their *Draft Industrial Biofuels Strategy* (2006). Graphs for each of the four scenarios are provided to facilitate the discussion. Each graph illustrates the annual potential for bioethanol production from maize in comparison with the amount of bioethanol needed to achieve the DME's biofuel target.

4.5.1 Baseline scenario results

The baseline scenario results for the potential production of bioethanol from maize in South Africa between 2008 and 2013 are graphically presented in Figure 4.7.

In this scenario, there is not enough maize available to produce 1.2 billion liters of bioethanol to achieve the DME's biofuel target in 2008. However, improvements in agricultural technologies result in increased maize yields and increased maize supply. Therefore, from 2009 onward enough maize is available for the production of bioethanol to achieve the DME's target.

[3] *Note that is possible that the product-demand growth rate for petrol can be even more than 1% per annum, although there is no proof or exact estimates for this.*

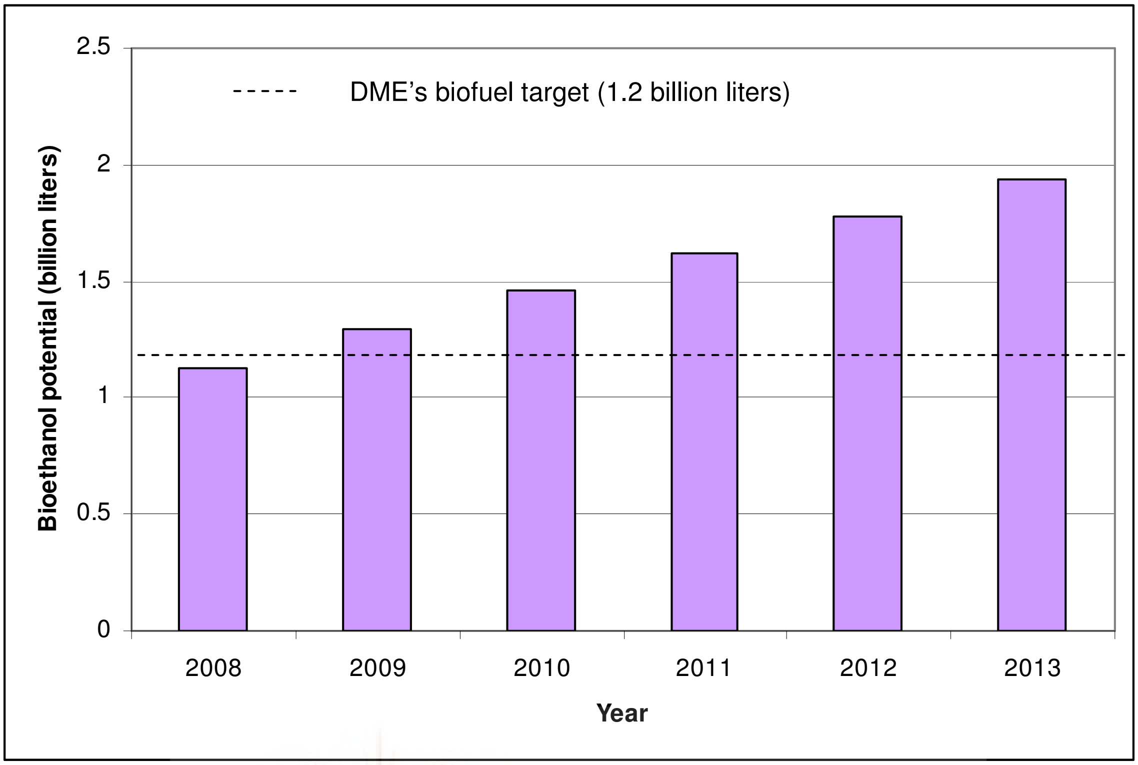

Figure 4.7: Baseline scenario results for bioethanol potential from maize

4.5.2 Best case scenario results

The best case scenario results for the potential production of bioethanol from maize in South Africa between 2008 and 2013 are graphically presented in Figure 4.8.

According to this scenario, more than enough maize is available for the production of bioethanol to achieve the DME's biofuel target. In fact, according to the best case scenario assumptions, maize supply is projected to continue to increase after 2013. However, an analysis of historic trends in maize yields show that this is unlikely. Maize yields will increase exponentially, after which the growth rate will decrease slightly and stabilise. In the long-term, the demand for bioethanol will continue to increase, while maize yields and the supply of maize stabilises and cease to increase. It is therefore not certain that bioethanol production from maize in South Africa is feasible in the long-term.

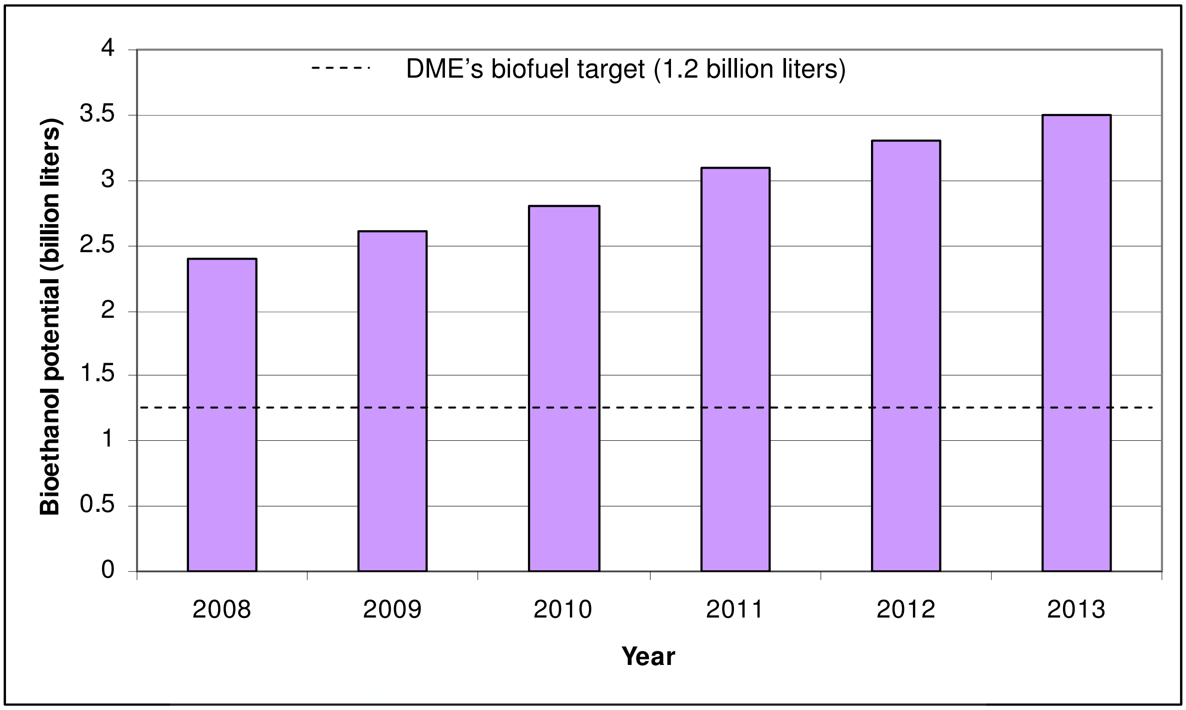

Figure 4.8: Best case scenario results for bioethanol potential from maize

4.5.3 Worst case scenario results

The worst case scenario results for the potential production of bioethanol from maize in South Africa between 2008 and 2013 are graphically presented in Figure 4.9.

In this scenario, enough maize is produced to achieve the DME's biofuel target of 1.2 billion liters of bioethanol from 2008 to 2010. However, decreasing maize yields results in less maize being available for the production of bioethanol and from 2011 onwards the availability of maize is insufficient to achieve the DME's target. If this trend persists, maize supply could decrease to a level where food security is threatened.

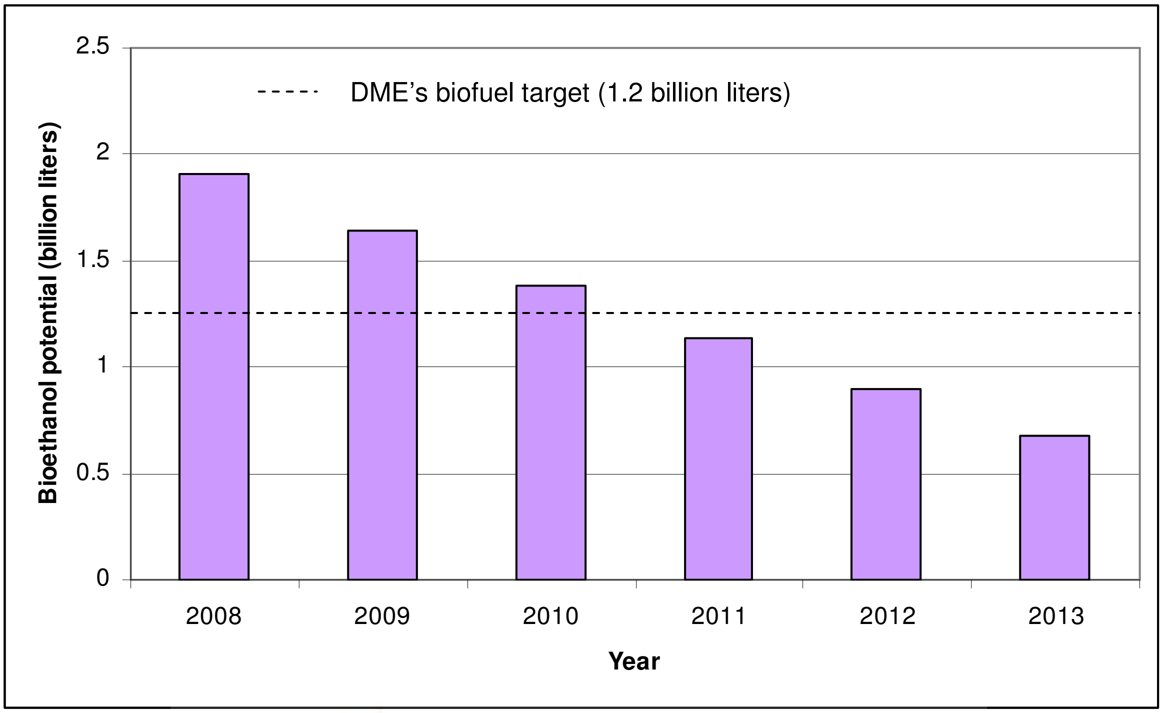

Figure 4.9: Worst case scenario results for bioethanol potential from maize

4.5.4 Rapid change scenario results

The rapid change scenario results for the potential production of bioethanol from maize in South Africa between 2008 and 2013 are graphically represented in Figure 4.10.

According to this scenario, the potential for bioethanol production from maize decreases from 2008 onwards. After 2011 the potential for bioethanol production is not sufficient to meet the DME's biofuel target of 1.2 billion liters and by 2013 only 827 million liters of bioethanol could be produced. The supply of maize will have to nearly double for enough maize to be available to meet the DME's biofuel target by 2013, without seriously threatening food security.

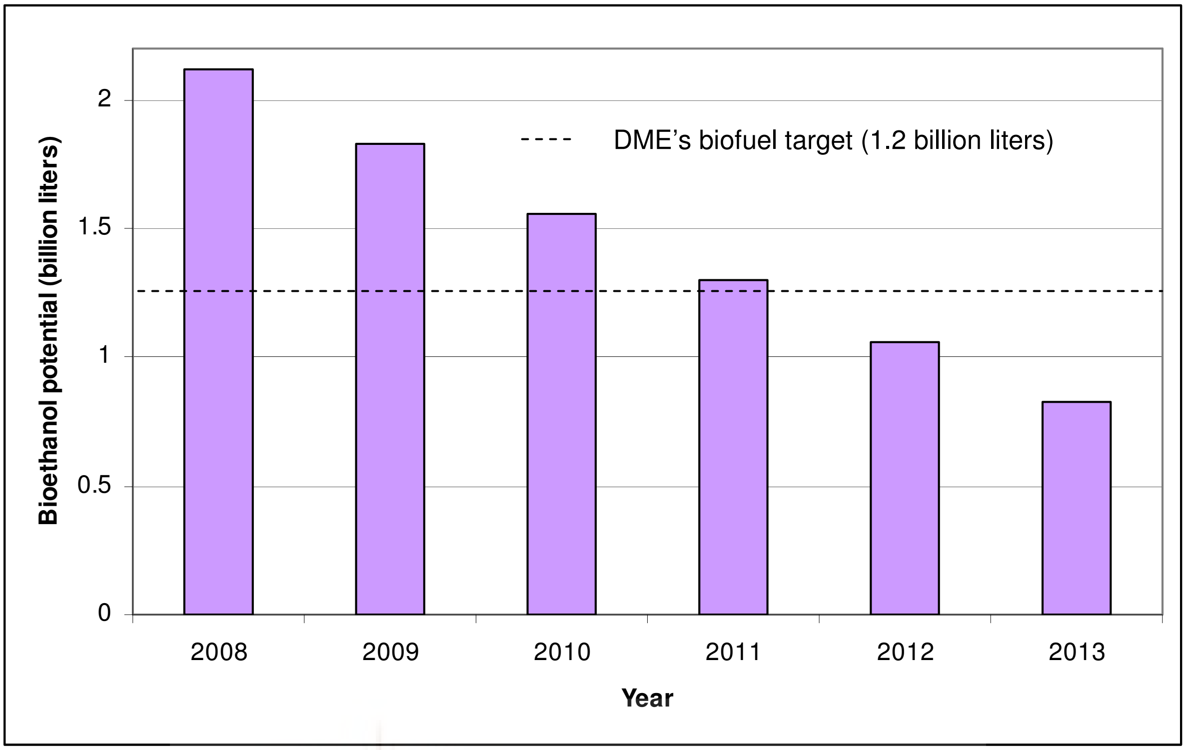

Figure 4.10: Rapid change scenario results for bioethanol potential from maize

4.6 Synthesis

The final results of the four bioethanol potential scenarios are compared in Figure 4.11. The baseline scenario allows a slow, but steady increase in the bioethanol potential for South Africa. However, the best case scenario proves to yield very optimistic results in comparison with the other three scenarios. The worst case scenario shows the fastest decrease in bioethanol potential between 2008 and 2013. In this scenario, bioethanol potential drops below that of the baseline by 2010 and below that of the rapid change scenario by 2013. The DME's biofuel target of 1.2 billion liters of bioethanol could be achieved for all four scenarios in 2009 and 2010. After 2010 the bioethanol potential decreases below the DME's target value for the worst case and rapid change scenarios.

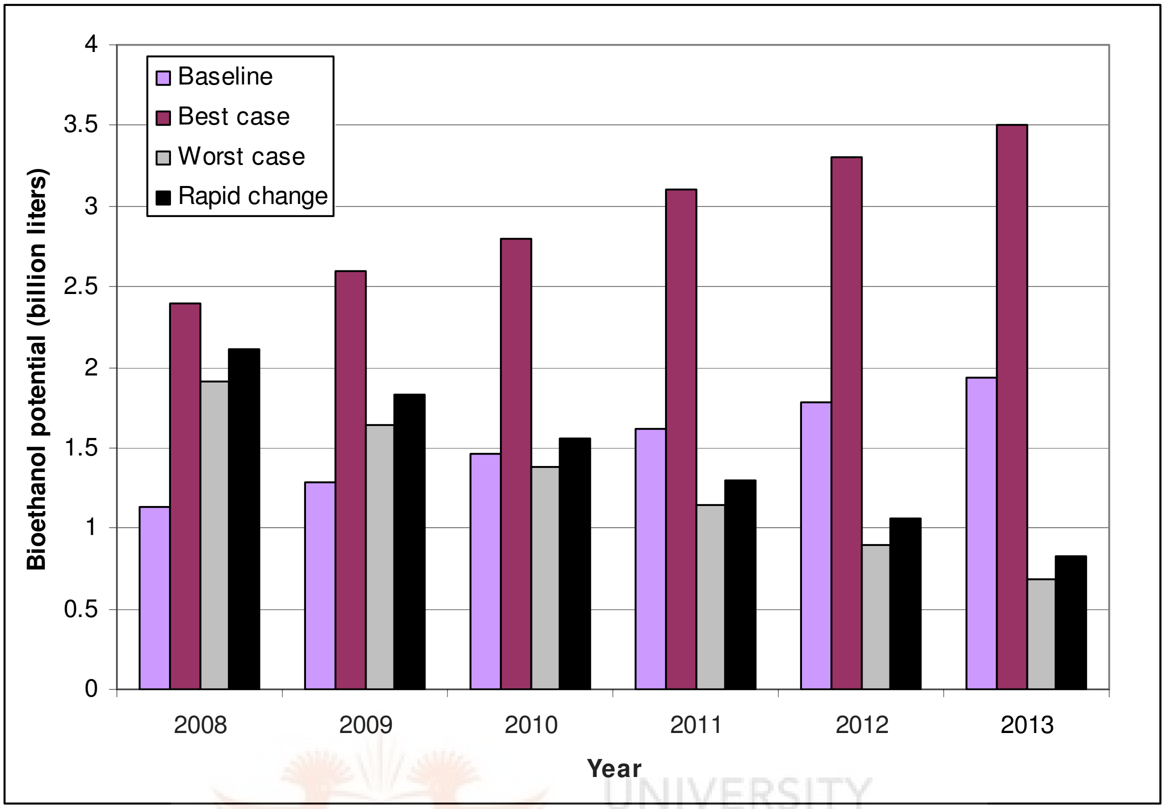

Figure 4.11: Comparison of scenario simulation results

4.7 Sensitivity analysis

The sensitivity analysis aims to clarify which of the three input factors of the bioethanol potential model (i.e. population size, available area and maize yield) contribute most to variability in the model outputs. This will help to determine the level of accuracy that is needed for the three input factors to make the bioethanol potential model useful and valid.

4.7.1 Population size

The population size input values for the bioethanol potential model were varied in two increments of 5% in the positive and negative direction. The results are summarised in Table 4.9. A 5% increase in the population size input values resulted in a 6.15% decrease in the bioethanol potential output values. Similarly, a change of 5% decrease in the population size input values resulted in a 6.15% increase in the bioethanol potential output values. A change of 6.15% in the bioethanol potential output values is of little consequence and therefore, variation in the population size input values does not have a significant impact on the bioethanol potential model.

Table 4.9: Sensitivity analysis results for population size

Population size	- 10 %	- 5 %	0 %	+ 5 %	+ 10 %
Bioethanol potential	+ 12.29 %	+ 6.15 %	0 %	- 6.15 %	- 12.29 %

4.7.2 Available land

The available land area input values were varied in two increments of 5% in the positive and negative directions. The results are summarised in Table 4.10. A 5% increase in the available land used for the cultivation of maize results in a 13.42% increase in the bioethanol potential and vice versa. A 13.42% change is more than that observed in the population size sensitivity analysis and is therefore believed to have a more significant impact on the bioethanol potential model.

Table 4.10: Sensitivity analysis results for available land

Available area	- 10 %	- 5 %	0 %	+ 5 %	+ 10 %
Bioethanol potential	- 26.84 %	- 13.42 %	0 %	+ 13.42 %	+ 26.84 %

4.7.3 Maize yield

Maize yield input values were varied in two increments of 5% in the positive and negative direction. The results are summarised in Table 4.11. The results are the same as for the available area sensitivity analysis. Variability in maize yields and the available area therefore have an equal amount of influence on the bioethanol potential model.

Table 4.11: Sensitivity analysis results for maize yields

Maize yield	- 10 %	- 5 %	0 %	+ 5 %	+ 10 %
Bioethanol potential	- 26.84 %	- 13.4 %	0 %	+ 13.4 %	+ 26.84 %

The two most important input factors that cause variability in the bioethanol potential model outputs are the available area for maize production and maize yields. In fact, there is a direct link between these variables brought about by the inherent structure of the bioethanol potential model. The effect of the available area and maize yields as input factors is more than double that of population size. However, a 13.4% change in the bioethanol potential brought about by a 5% change in the available area or maize yield is too little to threaten the validity of the bioethanol potential model and results.

4.8 Conclusion

The first aim of this chapter was to determine the availability of maize for the production of bioethanol in South Africa, using four different bioethanol potential scenarios. The second aim was to compare the results of each scenario with South Africa's biofuel target for 2013 stated in the *Draft Biofuels Industrial Strategy* (DME, 2006a:9).

Results of the baseline scenario showed that enough maize would be available to produce sufficient amounts of bioethanol to achieve the DME's biofuel target between 2009 and 2013. The best case scenario had very optimistic results and South Africa would be able to achieve the DME's biofuel target easily. However, the increased resources required may not be available and this would impact negatively on the projected maize production as set out in this scenario. The worst case scenario results proved that bioethanol potential will decrease below the DME's target by 2011. Rapid global climate change and the impact of the HIV/Aids pandemic in South Africa will lead to decreasing bioethanol potential and the DME's target would therefore not be achieved by 2013.

A sensitivity analysis was performed and results showed that population size does not cause significant variability in the bioethanol potential model results. However, changes in the available area and maize yields lead to a higher degree of variability in the model results and therefore need to be quantified to a high level of accuracy if the bieothanol potential model is to remain valid.

CHAPTER 5
ALTERNATIVES FOR A SUSTAINABLE ENERGY FUTURE FOR ROAD TRANSPORT IN SOUTH AFRICA

"In South Africa, transport fuels make up 30% of energy consumption (by energy content) and 70% (by value). Therefore the transport sector is an important energy sector to consider the development of renewable energy sources and technologies." (DME, 2007:6).

5.1 Introduction

The road transport sector accounts for approximately 80% of the liquid fuels utilised in South Africa per annum (DME, 2006b). To increase the supply of liquid fuels and improve energy security in South Africa, the DME aims to increase the use of biofuels to replace 4.5% of liquid road transport fuels by 2013 (DME, 2006a:9). This study investigated the potential of producing bioethanol from maize in South Africa in order to achieve a more sustainable energy future for road transport. However, several alternatives to fuel sustainable road transport have been identified, including the production of bioethanol from sugar cane, improvements in energy efficiency and cleaner fossil fuel technologies (Davidson, 2006:15). This chapter sets out to compare two sustainable road transport options, namely improvements in energy efficiency and the production of bioethanol from sugar cane, in line with the aim stated by the DME in their *Draft Biofuels Industrial Strategy* (2006a:9).

5.2 Improvements in energy efficiency

Energy efficiency has several environmental, economic and social advantages. Firstly, if fossil fuels are the primary energy source used, the consumption of less energy reduces the amount of greenhouse gases emitted into the atmosphere and delays the depletion of finite energy sources. Secondly, energy efficiency increases energy security by reducing the need to import energy sources. Lastly, it is one of the cheapest ways to provide energy services to the poor (Bennett, 2001:2; Spalding-Fecher, 2002:1099). Therefore, it is believed that improvements in energy efficiency are essential to achieving sustainable energy development in South Africa (Winkler *et al*., 2005:viii), especially when applied to the South African road transport sector (Bennett, 2001:3; DME, 2005:i).

South Africa recognised the benefits of improved energy efficiency in 2005, when the DME published their *Energy Efficiency Strategy*, with the aim to "…encourage sustainable energy sector development and energy use through efficient practices." (DME, 2005:4). In this strategy the DME set the goal to achieve energy efficiency savings of up to 9% in the road transport sector by 2015 (DME, 2005:16). This would be done primarily by encouraging the use of public transport and introducing efficiency standards for road vehicles (DME, 2005:16).

Could improvements in energy efficiency aid in the achievement of a sustainable and renewable energy future for road transport in South Africa? The future demand for road transport fuels, petrol and diesel, in South Africa as estimated by SAPIA (2007), is summarised in Table 5.1. Energy efficiency savings of up to 9% in the road transport sector by 2015 (DME, 2005:16) would thus translate into savings of approximately 1.1 billion liters of petrol and 857 million liters of diesel.

Table 5.1: Demand for petrol and diesel for road transport purposes in South Africa, 2010 – 2015 (Source: SAPIA, 2007)

Fuel	2010	2011	2012	2013	2014	2015
Petrol	11 737	11 854	11 973	12 093	12 214	12 336
Diesel	9 062	9 152	9 244	9 336	9 430	9 524
<u>Note:</u> *All figures listed as millions of liters. Figures estimated at a 1% product-demand growth rate per annum, as stated by SAPIA (2007).*						

Barriers to improving energy efficiency include the high dependency of the public on privately owned vehicles, wasteful energy consumption patterns and a general lack of investments in energy efficiency technologies (Schleich & Gruber, 2008:452; Gan, 2003:537). The implementation of efficiency measures further requires the support of governmental and non-governmental institutions (Davidson, 2006:20). However, unlike biofuels, there are no environmental barriers to the implementation of energy efficiency measures.

5.3 Bioethanol production from sugar cane

The South African sugar industry currently produces an average of 20 million tons of sugar cane per year, which is used to produce approximately 2.5 million tons of sugar. Only half of this is consumed domestically, while the other half is exported to the rest of Africa, North America, the Middle East and Asia (NDA, 2006:36).

What would happen if sugar surpluses are not exported, but rather used for the production of bioethanol in South Africa? The National Biofuels Task Team (2006:48) is of the opinion that the production of bioethanol from sugar surpluses shows considerable potential in South Africa. However, the National Biofuels Task Team does not provide sufficient quantitative information to support their conclusion. This study therefore uses data generated by the Bureau for Food and Agricultural Policy (BFAP, 2007a) to determine the potential for bioethanol production from sugar cane in South Africa.

In their baseline scenario for future agricultural production in South Africa, the BFAP predicted that South Africa will be able to produce approximately 2.3 million tons of refined sugar by 2012 (BFAP, 2007a:28). As shown in Table 5.2 the domestic consumption of sugar is expected to reach 1.3 million tons during the same period, resulting in sugar surpluses of nearly 1 million tons per annum.

Table 5.2: Sugar production according to the BFAP baseline scenario, 2008 – 2012 (Source: BFAP, 2007a:28)

Year	Area harvested (ha)	Sugar production (tons)	Sugar consumption (tons)	Sugar surplus (tons)
2008	321 000	2 462 000	1 293 000	1 169 000
2009	321 000	2 463 000	1 302 000	1 161 000
2010	320 000	2 320 000	1 313 000	1 007 000
2011	320 000	2 288 000	1 324 000	964 000
2012	319 000	2 289 000	1 337 000	952 000

One ton of refined sugar can be used to produce approximately 651.2 liters of bioethanol (National Biofuels Task Team, 2006:109). Therefore, the potential exists for South Africa to produce approximately 620.8 million liters of bioethanol from 952 000 tons of refined sugar in 2012, which is more than half the DME's target of 1.209 billion liters of bioethanol in 2013.

Other benefits of utilising sugar cane as bioethanol feedstock in South Africa include the use of byproducts (bagasse and molasses) to generate electricity and produce additional bioethanol (Braunbeck *et al.*, 1999:502). Each ton of processed sugar cane delivers enough bagasse to generate approximately 300 MW of electricity (Grad, 2006:56). Therefore, an additional 190 750 GWh of electricity can be produced from the 2 289 000 tons of sugar cane processed by 2012. This is approximately 19 times more than the DME's renewable energy target for 2013 (DME, 2004:iv).

Several implementation barriers must be overcome for a sugar cane bioethanol industry to be established in South Africa. Political barriers include the partial deregulation of the South African sugar industry and the redrafting of the *Sugar Act* of 1978 (EDC & IDC, 2007:27), while important environmental barriers relating to land, water and feedstock availability must be addressed (National Biofuels Task Team, 2006:16).

5.4 Synthesis

The production of bioethanol from sugar cane and the improvement of energy efficiency in South Africa show considerable potential. However, there are serious barriers to be overcome before these energy technologies can be implemented. Table 5.3 provides a summary of the comparative benefits and barriers mentioned above.

Table 5.3: Summary of the potential benefits and barriers of two comparative energy technologies in South Africa

Benefit/barrier	Improvements in energy efficiency	Bioethanol from sugar cane
Fuel savings	• 1.1 billion liters of petrol per annum by 2015 • 857 million liters of diesel per annum by 2015	• 620.8 million liters of petrol per annum by 2013
Electricity generation	• Not applicable for road transport	• 190 750 GWh by 2013
Political barriers	• Lack of energy efficiency standards and regulations	• Partial deregulation of the sugar industry • Redrafting of the *Sugar Act* of 1978
Social barriers	• High dependency of people on privately owned vehicles • Wasteful energy consumption patterns	• Lack of awareness on the potential benefits of a sugar cane bioethanol industry
Economic barriers	• General lack of investments	• High initial cost of establishing a sugar cane bioethanol industry • General lack of investments and capital
Environmental barriers		• Availability of land, water and feedstocks

It is clear that improving energy efficiency has greater potential to save transport fuels and thus help South Africa to achieve a sustainable and renewable energy future for road transport. One should take into account that the production of bioethanol from sugar cane will not only save transport fuels, but generate valuable electricity. Nonetheless, both technologies have important barriers that will have to be overcome for the technology to be implemented successfully.

This study therefore recommends that South Africa pursues the improvement of energy efficiency in road transport, as well as the establishment of a bioethanol industry using sugar cane as feedstock. This will require the overcoming of numerous political, social, economic and environmental barriers.

This section concludes with a quote by South Africa's previous Minister of Minerals and Energy:

> *"…Major energy savings can only be achieved through changes in people's behaviour, and that depends on informing them about what options exist…" (Mlambo-Ngcuka, 2005:i).*

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

"The main concern regarding food security revolves around the use of maize for ethanol production. It is for this reason that it has been proposed that maize for the production of bioethanol should be excluded in the initial phases of the strategy implementation. It is envisaged that bio-ethanol production from maize will be considered only once certainty on the ability of the currently under utilised land to produce has been ascertained and the necessary measures are in place to guard against extreme (industry linked) food inflation." (DME, 2007:14).

6.1 Introduction

Since the release of the *Draft Biofuels Industrial Strategy* in December 2006, the strategy received wide ranging criticism regarding issues such as food security, water availability, environmental sustainability and feedstock choices (DME, 2007:3). Changes were made and during the course of this study the DME released their final *Biofuels Industrial Strategy* (2007) with the aim to increase the use of biofuels to replace 2% of conventional transport fuels by 2013. This is 2.5% less than stated in the *Draft Biofuels Industrial Strategy.* More significantly, maize was to be excluded as potential feedstock for bioethanol production, until research proved otherwise (DME, 2007:3). This study indeed can be seen to be contributing to the required research effort.

The aim of this study was to determine the potential of using maize as feedstock to produce bioethanol in South Africa. For this purpose, six specific objectives were set and stated in Chapter 1. Subsequently, relevant and recently published biofuel literature was reviewed in Chapter 2, providing the reader with a basic understanding of biofuels and the issues underlying the successful identification of potential biofuel feedstocks. Taking these and other social, economic and environmental issues into account, a model for determining the potential for bioethanol production from maize in South Africa was developed in Chapter 3. The relevant data was gathered and prepared for input into this bioethanol potential model. The results were interpreted in Chapter 4 and a sensitivity analysis was performed to determine which of the social, economic and environmental input factors had the greatest impact on the model outputs. Chapter 5 provided short insights into the possible alternatives to achieving a more sustainable energy future for road transport in South Africa.

This chapter draws important conclusions regarding the potential of bioethanol production from maize in South Africa and consequently, identifies the limitations of the study and stipulates areas for possible further research.

6.2 Key findings

The key findings of this study are:

- Much of the recently published biofuel literature aims to quantify the amount of available land and feedstocks for biofuel production. These studies are usually performed at global geographical scales and this leads to generalised results.

- There are four key elements that influence the potential for bioethanol production from maize in South Africa, namely maize demand, maize supply, the demand for maize as biomaterial and the available land area. These elements interact with each other within South Africa's social, economic and natural environment, and form the basis of the bioethanol potential model developed in this study.

- Four bioethanol potential scenarios were formulated to provide an all-inclusive view regarding the study topic. The scenario results are summarised as follows:

  (i) The baseline scenario allows a slow, but steady increase in the potential bioethanol yield for South Africa. Approximately 4.6 million tons of maize would be available for the production of 1.9 billion liters of bioethanol by 2013;

  (ii) The best case scenario promises very optimistic results in comparison with the other three scenarios. More than 8.3 million tons of maize would be available for the production of 3.49 billion liters of bioethanol by 2013;

  (iii) The worst case scenario shows the fastest decrease in potential bioethanol yield between 2008 and 2013. Only 1.6 million tons of maize would be available to produce approximately 684 million liters of bioethanol in 2013;

  (iv) In the rapid change scenario only 1.964 million tons of maize would be available for the production of 827 million liters of bioethanol by 2013; and

  (v) The DME's biofuel target of 1.2 billion liters of bioethanol could be achieved for all four scenarios in 2009 and 2010. From 2011 onwards the bioethanol potential decreases below the DME's target value for the worst case and rapid change scenarios.

- The use of sugar cane for the production of bioethanol in South Africa is a feasible option. However, improvements in energy efficiency in the road transport sector show the most promising results. Such improvements could result in savings of 1.1 billion liters of petrol and 857 million liters of diesel per annum by 2015.

- Changes made to the *Draft Biofuels Industrial Strategy* (2006) include the lowering of the DME's biofuel target for 2013 from 4.5% to 2% of conventional transport fuels, as well as the exclusion of maize as potential feedstock for bioethanol production. Based on the findings of this study, the changes made to the *Draft Biofuels Industrial Strategy* (2006) seem valid and well founded.

6.3 Limitations

Four main types of limitations were identified in this study, including limitations pertaining to scenario planning, model development, data quality and the main assumptions.

Firstly, this study made use of scenario planning as a tool for helping us understand the future. Unfortunately, scenario planning is characterised by an inherent degree of uncertainty regarding the future social, economic and natural environment in which these scenarios will play out. The matrix approach used in scenario development further tends to oversimplify these future environments. Uncertainty was partly reduced by analysing historic trends, focusing on elements with a high degree of predictability and by adopting a short-term focus in scenario development, as discussed in Section 4.2.1. Unfortunately, sudden events with unpredictable consequences can occur any day and therefore, a certain level of uncertainty will always remain.

Secondly, the development of the four bioethanol potential scenarios was further hampered by certain model limitations. One such model limitation is the use of only three main variables (i.e. population size, land availability and maize yields) for the development of the bioethanol potential model. Other variables, such as the availability of water for irrigation purposes, soil fertility and carrying capacity, the availability of fertilisers and the impact of international agricultural markets, were not taken into account during model development. These variables were deliberately excluded in order to simplify model simulation. However, it is recognised that these variables could have a noticeable influence on the availability of maize for the production of bioethanol.

Thirdly, there are some data limitations in the study. Much data were derived from other studies, including land capability data by Schoeman and Van der Walt (2006); maize yield data by the Bureau for Food and Agricultural Policy (BFAP, 2007b) and the national Crop Estimates Committee (CEC, 2007); and population data by Statistics South Africa (StatsSA, 2007) and Dorrington *et al*. (2006). The results of this study are therefore dependent on the quality of the data generated in the above mentioned studies. A further data limitation is that the data reflects the current level of knowledge and technology. New information generated by future research and development activities could prove the data inaccurate and redundant. It is known that scenario planning tends to ignore such new information and therefore, the accuracy of the results is restricted (Van der Heijden, 2005:93).

Lastly, several assumptions were made during the course of the study. These assumptions include those pertaining to food security; genetically modified maize; improvements in agricultural technology; and international trade in agricultural products. Some simplifying assumptions in the bioethanol potential model may result in an under- or overestimation of South Africa's true bioethanol potential from maize.

6.4 Areas for future research

In a study by the Energy Development Corporation and the Industrial Development Corporation of South Africa (EDC & IDC, 2006), three main areas for future biofuel research were identified, namely the social, economic and environmental impacts of biofuel production in South Africa. In response to their study, the National Biofuels Task Team (2006) compiled a report that aimed to supply information regarding the areas that will require future research. To avoid repetition of the facts stated by the National Biofuels Task Team (2006), this section summarises only some of the issues identified by the EDC and IDC (2006). Other areas for future biofuel research identified during the course of this study will be added and explained in detail.

6.4.1 Social issues

The EDC & IDC (2006:28) identified two main social issues that require further research before a South African biofuel industry can be established. The most important social issue identified by the EDC & IDC (2006) pertains to the creation of new employment opportunities in the biofuel sector in South Africa. Studies by Austin *et al*. (2003), Prasad and Visagie (2005), Winkler *et al*. (2005) and Sugrue (2007) shed some light on this issue, all noting that biofuel production could contribute significantly to the creation of new jobs in the agricultural, biomass conversion and transport industries in South Africa.

However, none of these studies focus solely on biofuel production and their social impacts. Rather, these studies consider and compare different renewable energy technologies and their potential for improving South Africa's social environment. It is recommended that future research should expand on the above mentioned studies by qualitatively assessing and quantitatively determining the impacts of bioethanol production from maize on employment in South Africa.

A further social issue identified by the EDC & IDC (2006) pertains to the impact of biofuel production on domestic food security in South Africa. As discussed in Chapter 1, limited amounts of arable land and other environmental restrictions to agriculture already pose a threat to food security in South Africa. The use of land and agricultural resources to produce biofuels in South Africa will only worsen the situation. Therefore, the DME stated in the final *Biofuels Industrial Strategy* (DME, 2007:3) that food security is probably the most sensitive issue that needs further consideration before a large-scale biofuel industry could be established in South Africa.

One of the underlying aims of this study was to determine the impact of bioethanol production from maize on domestic food security in South Africa. However, further research is needed to determine the impact of biofuel production from different crops and on different scales on domestic food security. This will help policy formulators to develop policies that will minimise the negative impacts of biofuel production on food availability, thereby ensuring the safe and secure supply of food to all South Africans.

6.4.2 Economic issues

Several economic issues were identified by the EDC & IDC (2006:29), such as issues pertaining to the regional and macro-economic impact of employment creation in the biofuel sector and how the rural poor and small-scale subsistence farmers will be affected by biofuel production.

A comprehensive analysis on all economic issues arising from bioethanol production from maize in South Africa was conducted by the Bureau for Food and Agricultural Policy (BFAP, 2005). Other economic investigations include studies on the impact of macroeconomic variables on biofuel production in South Africa (BFAP, 2007c), the economic benefits of biofuel production for South African farmers (Botha, 2007) and the impact of biofuel production on the rural poor in South Africa (Sugrue, 2007).

This study did not incorporate economic factors in assessing the potential for bioethanol production from maize in South Africa. This is a significant shortcoming and it is therefore recommended that future research should aim to refine the results of this study and the above mentioned studies. This will provide all relevant stakeholders (e.g. policy formulators, non-government and non-profit organisations, investors and farmers) with detailed information on the economic risks and benefits of biofuel production. Stakeholders need this information to make effective decisions regarding the content of South African biofuel policy and legislation, as well as the level of private and public investment in the biofuel industry.

6.4.3 Environmental issues

The EDC & IDC (2006:29) identified a need to determine the size and location of land with suitable climatic and soil properties for the production of biofuel crops, as well as a need to identify marginalised land that may be in danger of overexploitation and land degradation. The available amount and location of water resources for the irrigation of biofuel crops also need to be determined (EDC & IDC, 2006:29).

Very little has been done with respect to determining the extent and location of environmental impacts arising from biofuel production in South Africa. Initial research only focused on broadly identifying the possible environmental impacts of biofuel production. Future research should aim to quantitatively determine the amount of environmental resources that will be needed to establish a large-scale biofuel industry in South Africa. Research should also qualitatively assess the impacts arising from the level of resource extraction and use. This will allow planners and policy formulators to define an appropriate scale for biofuel production in South Africa, thereby reducing the negative environmental impacts and enhancing positive environmental impacts.

6.5 Conclusion

Global climate change is placing increasing pressure on South Africa's limited and fragile agricultural land. The projected decrease in annual rainfall over the South African interior will cause maize yields to decrease, thus seriously threatening domestic food security. Population growth and the increasing demand for maize as food and animal feed is further exacerbating the problem.

For these reasons, the production of bioethanol from maize in South Africa is a very contentious issue. In the *Draft Biofuels Industrial Strategy* (2006) the DME aimed to increase the use of biofuels to 4.5% of the total supply of road transport fuels by 2013. This translates to the production of 1.209 billion liters of bioethanol by 2013.

One can now attempt to answer the question: *What is the future potential for bioethanol production from maize in South Africa to 2013 under different social, economical and environmental conditions?*

This study made use of the scenario planning method to determine the potential for bioethanol production from maize in South Africa. Results of the scenario simulation showed that South Africa will be able to produce enough maize to meet the DME's biofuel target of 1.2 billion liters of bioethanol for all scenarios between 2009 and 2010. From 2011 onwards, the bioethanol potential decreases below the DME's target value in both the worst case and rapid change scenarios.

To conclude, the production of bioethanol from maize in South Africa will therefore have various social, economic and environmental consequences for the country's agricultural sector. The depletion of domestic maize supplies will seriously threaten food security and consequently, increase the country's dependence on maize imports. This will not only affect the country's maize producing regions, but spread throughout South Africa as the demand for agriculturally productive land for maize production increases. Domestic food security is at risk and South Africa will have to resort to other energy technologies to achieve a sustainable and renewable energy future for road transport.

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APPENDIX A

Table A.1: Detailed simulation results for the baseline scenario

Year		2008	2009	2010	2011	2012	2013
Population size (x 1000)		48 395.5	48 947.2	49 505.2	50 069.6	50 640.3	51 217.6
Food demand (x 1000 t)		3 957.4	4 018.5	4 080.2	4 142.7	4 205.9	4 269.8
Biomaterials (x 1000 t)		3 500.0	3 500.0	3 500.0	3 500.0	3 500.0	3 500.0
Total demand (x 1000 t)		7 457.4	7 518.5	7 580.2	7 642.7	7 705.9	7 769.8
Maize yield (tons/ha)	**White**	2.660	2.780	2.900	3.020	3.140	3.260
	Yellow	3.123	3.253	3.383	3.513	3.643	3.773
Available area (x 1000 ha)	**White**(1)	2 340	2 340	2 340	2 340	2 340	2 340
	Yellow(2)	1 260	1 260	1 260	1 260	1 260	1 260
Total supply (x 1000 t)		10 159.4	10 604.0	11 048.6	11 493.2	11 937.8	12 382.4
Availability (x 1000 t)		2 702.0	3 085.5	3 468.4	3 850.5	4 231.9	4 612.6
Conversion efficiency (liters/ton)		421	421	421	421	421	421
Potential (x 1000 liters)		1 137 541	1 299 006	1 460 177	1 621 052	1 781 627	1 941 898

Notes: (1) 65% of total available area
(2) 35% of total available area

Table A.2: Detailed simulation results for the best case scenario

Year		2008	2009	2010	2011	2012	2013
Population size (x 1000)		48 395.5	48 947.2	49 505.2	50 069.6	50 640.3	51 217.6
Food demand (x 1000 t)		3 957.4	4 018.5	4 080.2	4 142.7	4 205.9	4 269.8
Biomaterials (x 1000 t)		3 500.0	3 500.0	3 500.0	3 500.0	3 500.0	3 500.0
Total demand (x 1000 t)		7 457.4	7 518.5	7 580.2	7 642.7	7 705.9	7 769.8
Maize yield (tons/ha)	**White**	2.660	2.780	2.900	3.020	3.140	3.260
	Yellow	3.123	3.253	3.383	3.513	3.643	3.773
Available area (x 1000 ha)	**White**[(1)]	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5
	Yellow[(2)]	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5
Total supply (x 1000 t)		13 179	13 756	14 332	14 909	15 486	16 063
Availability (x 1000 t)		5 722	6 237	6 752	7 267	7 780	8 293
Conversion efficiency (liters/ton)		421	421	421	421	421	421
Potential (x 1000 liters)		2 408 790	2 625 888	2 842 692	3 059 200	3 275 408	3 491 313

Notes: [(1)] 65% of total available area
[(2)] 35% of total available area

Table A.3: Detailed simulation results for the worst case scenario

Year		2008	2009	2010	2011	2012	2013
Population size (x 1000)		48 395.5	48 947.2	49 505.2	50 069.6	50 640.3	51 217.6
Food demand (x 1000 t)		3 957.4	4 018.5	4 080.2	4 142.7	4 205.9	4 269.8
Biomaterials (x 1000 t)		3 500.0	3 500.0	3 500.0	3 500.0	3 500.0	3 500.0
Total demand (x 1000 t)		7 457.4	7 518.5	7 580.2	7 642.7	7 705.9	7 769.8
Maize yield (tons/ha)	**White**	2.395	2.259	2.130	2.009	1.894	1.786
	Yellow	2.891	2.793	2.698	2.606	2.518	2.432
Available area (x 1000 ha)	**White**(1)	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5
	Yellow(2)	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5
Total supply (x 1000 t)		11 996.4	11 421.3	10 875.3	10 356.8	9 864.5	9 396.8
Availability (x 1000 t)		4 539.0	3 902.9	3 295.1	2 714.1	2 158.6	1 627.0
Conversion efficiency (liters/ton)		421	421	421	421	421	421
Potential (x 1000 liters)		1 910 935	1 643 103	1 387 225	1 142 649	908 763	684 987

Notes: (1) 65% of total available area
(2) 35% of total available area

Table A.4: Detailed simulation results for the rapid change scenario

Year		2008	2009	2010	2011	2012	2013
Population size (x 1000)		48 545.6	48 855.2	49 147.2	49 418.6	49 670.2	49 904.2
Food demand (x 1000 t)		3 974.0	4 008.3	4 040.6	4 070.6	4 098.5	4 124.4
Biomaterials (x 1000 t)		3 500.0	3 500.0	3 500.0	3 500.0	3 500.0	3 500.0
Total demand (x 1000 t)		7 474.0	7 508.3	7 540.6	7 570.6	7 598.5	7 624.4
Maize yield (tons/ha)	**White**	2.511	2.370	2.238	2.112	1.994	1.882
	Yellow	2.982	2.848	2.720	2.598	2.481	2.369
Available area (x 1000 ha)	**White(1)**	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5	3 035.5
	Yellow(2)	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5	1 634.5
Total supply (x 1000 t)		12 500	11 853	11 241	10 660	10 110	9 589
Availability (x 1000 t)		5 026	4 345	3 700	3 090	2 512	1 964
Conversion efficiency (liters/ton)		421	421	421	421	421	421
Potential (x 1000 liters)		2 115 856	1 829 320	1 557 826	1 300 763	1 057 383	826 910

Notes: (1) 65% of total available area
(2) 35% of total available area