LIFE CYCLE ASSESSMENT OF MAIZE COBS AND OTHER ENERGY CROPS FOR ENERGY PRODUCTION COMPARED TO CONVENTIONAL METHODS

MSc RESEARCH REPORT

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ABSTRACT

Coal is currently the most widely used feedstock for electricity generation in the world. According to Eskom, about 77% of South Africa's energy needs are met by coal power. Emissions related to this energy source include nitrogen and sulfur oxides, heavy metals, radioactive elements, organic compounds, greenhouse gases and a significant amount of ash. This results in pollution of air, water and land. The demand for electricity continues to increase with rapid economic development and population growth. It is therefore necessary to explore and assess alternative methods of energy production.

The conversion of biomass to electricity could play a vital role in reducing the dependency on coal power in South Africa. As such, the use of maize cobs, as well as other agricultural residues, could offer promising opportunities for renewable energy production. However, there are few environmental impact studies in South Africa addressing the production or preparation phase of energy feedstocks for such purposes.

This study used Life-cycle Assessment (LCA) to evaluate the environmental burdens associated with the production of maize (and wheat) and extraction of maize cobs/stover (and wheat stalks) for the purpose of producing electricity through gasification. The assessment includes the entire life cycle of the energy feedstocks, agricultural activities, transportation and conversion into electricity, but excludes seed production, electricity distribution and waste management. The impacts associated with the production and use of maize cobs in electricity production are compared with those of maize stover and wheat stalks. The study also compares the environmental impacts of these processes with coal power.

The results show that the areas of environmental concern for the production of biomass electricity include fossil depletion, climate change, particulate matter formation and land occupation. Transportation and gasification of biomass feedstock contributes the most towards all environmental impacts. The impacts associated with wheat stalks and maize stover production are higher than those of maize cobs production. The environmental burdens associated with the conventional method of electricity generation in South Africa are over 90 % higher than those from producing electricity through gasification of maize cobs. The results

also suggest that generation of electricity form maize cobs has less environmental impacts than the generation of electricity using maize stover or wheat stalks; and coal power.

To improve the environmental performance of the biomass energy sector, improvements in agricultural practices must be implemented. For this, further research on fertilization, water use, agricultural practices, land transformation, biomass conversion technologies and transportation must be conducted.

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ABBREVIATIONS

AEMFC	African Exploration Mining and Finance Corporation
ALCA	Attributional Life Cycle Assessment
ARC	Agricultural Research Council
ANC	African National Congress
BASF	Baden Aniline and Soda Factory
BFAP	Bureau for Food and Agricultural Policy
BMG	Bearing Man Group
CFC	Chlorofluorocarbons
CGIAR	Consortium of International Agricultural Research Centers, formerly; Consultative Group for International Agricultural Research
CLCA	Consequential Life Cycle Assessment
CSIR	Council for Scientific and Industrial Research
DAFF	Department of Agriculture, Forestry and Fisheries
DME	Department of Minerals and Energy
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
IPA	International Police Association
ISO	International Organization for Standardization
LAN	Limestone Ammonium Nitrate
LCA	Life Cycle Assessment
LCCS	Land Cover Classification System
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAP	Mean Annual Precipitation
MOP	Muriate of Potash
MRD	Mineral Resource Depletion
NDP	National Development Plan
NER	National Energy Regulator
NGO	Non-Governmental Organization

NMVOC	Non-methane volatile organic compound
NPSH	Net Positive Suction Head
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
PCC	Pulverised coal combustion
SA	South Africa
SABI	Suid Afrikaanse Besproeiingsinstituut (South African Irrigation Institute)
SADEC	Southern African Development Community
SAGIS	South African Grain Information Service
SANEA	South African National Energy Association
SARB	South African Reserve Bank
SETAC	Society of Environmental Toxicology and Chemistry
SGR	Stover-to-grain ratio
SSP	Single Super Phosphate
UNFCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
WCI	World Coal Institute

NOMENCLATURE

A	Surface area	(m2)
AW	Available water	(mm)
AWD	Allowable water depletion	(%)
AR	Application rate	(mm/hr)
CGR	Cob-to-grain ratio	
CWR	Crop water requirement	(mm/day)
D	Diameter	(m)
$\mathbf{EC_e}$	Salt sensitivity	(mS/m)
$\mathbf{EC_w}$	Electrical conductivity	(mS/m)
ERD	Effective root depth	(mm)
$\mathbf{ET_c}$	Crop evapotranspiration	(mm/day)
$\mathbf{ET_0}$	Reference evapotranspiration	(mm/day)
GIR	Gross irrigation requirement	(mm/cycle)
h	Head or pressure head	(m)
$\mathbf{K_c}$	Crop factor	
L	Length	(m)
LR	Leaching ratio	
NIR	Nett irrigation requirement	(mm/cycle)
P	Power or Rainfall	(kW) or (mm)
$\mathbf{P_e}$	Effective rainfall	(mm)
$\mathbf{P_W}$	Percentage wetted area	(%)
Q	Flow rate	(m^3/hr)
$\mathbf{q_e}$	Emitter discharge	(l/hr)
R	Yield	(t/ha)
RAW	Readily available water	(mm)
S	Spacing	(m)
SGR	Stover-to-grain ratio	
t	Time	(days)
V	Volume	(m^3)
WHC	Water holding capacity	(mm/m)

Greek letters

α	Percentage allowable water depletion
η	Efficiency

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1. INTRODUCTION

1.1 Background

Maize or corn (Zea mays) is a cereal crop that is grown around the world in a range of environments. Maize is the most produced grain crop in the world and has about 50 species with a variation of textures, colours, grain sizes and shapes. The most common types of maize are white, red and yellow, with the yellow and white types most preferred. Maize has become one of Africa's principal food crops since it was introduced in the 1500s (McCann, 2005). The grains contain vitamins, A, C and E, essential minerals, proteins and carbohydrates. They are also rich in dietary fibre. South Africa is the second largest producer of maize in Africa, producing about eight million tons of grain per year (du Plessis, 2003).

Energy, water and food are the underlying support of the economy of any country, and a possible instability in one of these three structures will have a direct negative influence on the other two. According to Stats SA (2015), South Africa's economic growth slowed down in 2014 to 1.5 % from a 2.2 % growth in 2013. The report further indicated that the fastest growing industry was agriculture and that the mining and the electricity industries (electricity, gas and water) weakened by 1.6 % and 0.9 % respectively. There is a relationship between food, energy and water systems in the perspective of economic sustainability and security in SA (Brent, 2014). The increased pressure on these systems has resulted in progressive depletion of conventional fossil fuels and an increase in energy consumption and greenhouse gas (GHG) emissions (Singh *et al*, 2013).

There is an increasing need to produce sustainable energy based on renewable sources in order to replace fossil-based fuels. This will help to reduce GHG emissions and reduce dependence on other countries (Singh and Olsen, 2012; Pant *et al*, 2012). Furthermore, Aleklett and Campbell (2003) has reported that the global production of oil and gas is approaching its maximum and that the world is "finding one new barrel of oil for every four it consumes". Due to these critical issues regarding sustainability, environment and energy security, there is an increasing need to move toward alternative sustainable, renewable, efficient and cost-effective energy sources with lesser emissions (Prasad *et al*, 2007; Singh and Olsen, 2012).

Life Cycle Assessment (LCA) of renewable energy sources is fundamental in assessing the sustainability of the above-mentioned sources. Due to the differences in available resources, climate, social, environmental and economic conditions, LCA can be used as a tool to evaluate the sustainability of energy sources on the basis of their local conditions. This study uses LCA to assess the environmental sustainability of using maize cobs and other energy crops (i.e. maize stover and wheat stalks) for production of renewable energy.

1.2 Problem statement

The increasing energy demand and impending population growth highlight a need for solutions that will help increase the supply of energy and simultaneously, ensure food security. Biomass is a very promising solution for this, however, literature shows that there has been a lack of confidence as well as controversy around biomass energy (Zilberman *et al*, 2010; Fajardy and Mac Dowell, 2017). This is mainly due to the efficiency of biomass energy generation systems, the inconsistent feedstock yield and more especially their direct and indirect land use change. The use of biomass for energy production also raises concerns regarding loss of biodiversity, food security and water conservation.

In recent years, the United Nation's Framework Convention on Climate Change (UNFCCC), as well as other regulatory bodies, have been set up to encourage individuals and organizations to investigate and implement new environmental policies, adapt to new sustainable technologies and engage more in research and development. As a result, interest in the renewable energy industry has grown.

The increasing energy demand and concerns regarding resource depletion, GHG emissions and global warming are the main influences of the renewable energy industry. It is evident that global organizations should inforce policies that will be able to secure energy supply while mitigating climate change. Agricultural biomass for energy production/generation can play an important role in ensuring that society complies with these policies.

There are uncertainties with regards to the availability of biomass and their energy potential. It is therefore important to study and understand how agricultural practices can influence biomass energy and eliminate these uncertainties. Biomass energy has the potential to reduce global dependence on fossil fuels. However, their sustainability requires understanding of the environmental impacts associated with the production of biomass energy, compared to conventional fossil fuels.

1.2.1 Research objectives

The main objective of the project is to study the life cycle of maize cobs as feedstock for the production of electricity using the gasification process. The project also aims at studying the life cycle of other energy crops, i.e. maize stover and wheat stalks for the purpose of producing electricity using the same method mentioned above. The environmental burdens associated with the conventional method of electricity production is also studied.

Based on the International Organization for Standardization, ISO 14040:2006 guidelines, the purpose of this research project is to use life cycle assessment as a tool to evaluate the environmental burdens associated with the production of maize and extraction of maize cobs for the purpose of producing energy (electricity) through gasification. This is done by identifying and quantifying energy and materials used and wastes released to the environment. The impact of those energy and materials used and releases to the environment are assessed and opportunities to effect environmental improvements are identified and evaluated. The assessment includes the entire life cycle of the maize cobs, agricultural activities, manufacturing, transportation, delivery and use of raw material and inputs and the use of the maize cobs as feedstock for production of energy.

The specific objectives of this project are, therefore, to use life cycle assessment as a tool to:

- determine the environmental impacts of producing maize and extracting maize cobs for the purpose of producing electricity using the gasification process;
- study the environmental impacts of producing and using maize stover, and wheat stalks for the purpose of producing electricity through the process of gasification;
- study the environmental impacts associated with the conventional method of electricity production; and
- compare and analyse the three processes based on their environmental impacts.

1.3 Research methodology

The overall scope of this research project is to gain information about all gaseous, liquid and solid emissions involved in the production of maize cobs (and maize stover and wheat stalks) for energy production. This information will then guide decision making in the bioenergy production sector, with regards to the suitability and diversity of maize and wheat (and possibly other energy crops) in bioenergy compared to the conventional method of energy production.

The primary function of maize cobs and of other energy crops for this project is their use as feedstock for electricity production using gasification. The functional unit can be defined as 1 kWh of electricity produced by the specific energy crop. The reference flows can then be defined as the quantity (in kg) of crop residue that needs to be extracted in order to produce 1 kWh of electricity. The study follows the following technique, adapted from ISO 14000:2006 standards as well as SimaPro (an LCA software package) guidelines:

- Goal and scope definition
- Life cycle inventory
- Life cycle impact assessment
- Interpretation of results

1.4 Report outline

This report is divided into five chapters, which are briefly described below:

Chapter 1: Introduction
Gives a background to the research topic and outlines the research objectives. The methodology used to conduct the research is also outlined in this chapter.

Chapter 2: Literature review
This chapter serves as a literature review of the maize crop. A detailed description of the maize plant is given. The chapter highlights the production and market trends of maize production in South Africa. The useful products of the crop and its energy potential are described. A

literature review of electricity production, supply and demand in South Africa is presented. It explains how electricity is supplied and consumed in South Africa.

The chapter also gives details of how maize residues can be used for electricity production. This chapter also serves as a literature review of life cycle assessment. The subject is defined with details of how it was developed as well as its main characteristics. The methodology to be used in this study is explained in this chapter.

Chapter 3: Life cycle assessment of maize cobs for electricity generation
The life cycle assessment of the system under study is performed by following the outlined methodology. Background data is highlighted and used to calculate inventory data. The results are presented and interpreted in this chapter.

Chapter 4: Comparative life cycle assessment
The inventory data used for the conventional method and wheat stalks system are explained. The chapter also compares the system under study with alternative biomass systems as well as the conventional method of electricity production in South Africa.

Chapter 5: Conclusion and recommendations
Recommendations for improvement and for further research are given in this chapter.

2. LITERATURE REVIEW

2.1 Maize

2.1.1 Botanical description

The maize plant (Figure 2.1) has an amply branched, fine root system. The total root length can reach 1 500 m under optimal conditions (du Plessis, 2003). The stable root system consists of prop and adventitious roots. Four to six adventitious roots develop in a circlet of roots from nodes below the soil surface. From the first to the third aerial node, prop roots grow into bands after tessling. Prop roots perform two functions, which are taking up nutrients and providing support to the plant. In young plants, root hairs occur and aid the absorption of water and nutrients by increasing the surface area that is exposed to soil (du Plessis, 2003).

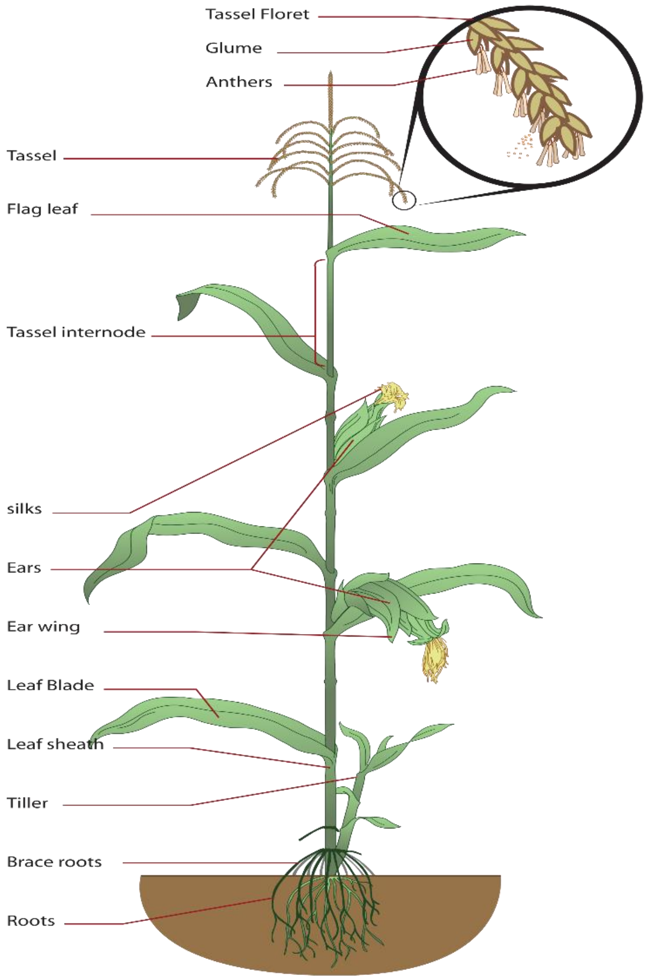

Figure 2.1 Maize plant diagram

Source: du Plessis (2003)

Eight to twenty spirally arranged leaves may form on the stem. These leaves occur interchangeably in two opposite rows on the stem. The maize leaf is a typical grass leaf with ligules, auricles, a sheath and a blade. The leaf is supported by a prominent mid-rib along its entire length. Along the leaf surface, stomata occur in rows with more occurring underneath than on the upper surface of the leaf (Towers, 1830). During moist conditions, motor cells on the upper surface absorb water, become turgid and unfold the leaf. During warm, dry weather, the cells lose their turgor and leaves curl inwards to expose a smaller surface to evaporation (du Plessis, 2003).

The maize stem is cylindrical, solid and clearly divided into nodes and internodes; it may grow to heights ranging from 0.6 m to more than 5 m and have eight to 21 internodes (Goodman and Ennos, 1998). Tillers may develop from nodes below the soil surface. On the eighth node above the soil surface, a bud occurs which has a lateral shoot that bears the main ear (cob). The maize ear or cob is the spiked part of the maize plant that contains the kernel. It ends one or more lateral branches, halfway up the stem (Nielsen, 2000). The ear is enclosed by bracts. Receptivity to pollen lasts for about three weeks, but starts to decrease after the tenth day (du Plessis, 2003).

The maize kernel consists of an embryo, a pericarp, a tip cap and an endosperm. The pericarp and tip cap enclose the kernel. The endosperm contains the carbohydrates. The embryo contains the parts that give rise to the next generation. Kernels can be of flint or dent types (Towers, 1830). Flit kernels can look round or flat and contain translucent starch, with a small part of soft starch in the middle. The dent kernel has a dented crown. During drying, the softer starch in the middle of the kernel shrinks faster than the outer more translucent sides (Goodman and Ennos, 1998).

2.1.2 Growth and development of maize

The successful production of maize depends on proper application of environmentally sustainable inputs as well as agricultural production. The inputs include soil tillage, adapted cultivars, fertilization, plant population, harvesting, disease and weed control and marketing and financial resources. Maize is an annual crop that requires 400 to 600 mm of water per season (Krishna, 2013). Every millimetre of water yields about 15 kg of grain per hectare.

The water is mainly assimilated from soil moisture reserves. At maturity, each maize plant will have used up about 250 litres of water (du Plessis, 2003). Plants also take up nutrients such as phosphorus, nitrogen and potassium from the soil. The yield per hectare of maize also depends on the plant's effective utilization of sunlight.

2.1.3 Production of maize in South Africa

According to the Department of Agriculture, Rural Development, Land and Environmental Affairs (DAFF) (2013), South Africa produces about 48 % of white maize, which is used primarily for human consumption, and 52 % of yellow maize for animal feed. The maize industry serves as both an employer and an earner of foreign currencies, because it also serves as raw material for manufactured products such as paper, paint, textiles, food and medicine. Maize can also be processed into fuel (ethanol) or starch. South Africa exports maize to Japan, Zimbabwe, Iran, Kenya, Venezuela, Malaysia and Zambia. Maize products are exported to Mozambique, Zambia and Angola. The DAFF report also indicated that for the past five years, maize has been the largest contributor towards the gross value of grain crops, with an amount of R 23 814 million for the 2012/13 financial year.

2.1.3.1 Production trends

There are about 9 000 commercial maize farmers in South Africa, producing about 10 million tonnes of maize per year on approximately 3 million hectares of land (Batidzirai *et al*, 2016). Maize yield varies from year to year, and is highly dependent on climatic conditions and management practices, amongst other factors. Over 80 % of maize in South Africa is produced on dry land, the rest is under irrigation. SAGIS (2014) reported about 2 million tonnes of irrigation maize yield per year on 230 000 hectares of land. The figure below shows the maize production trends in SA over the past two decades.

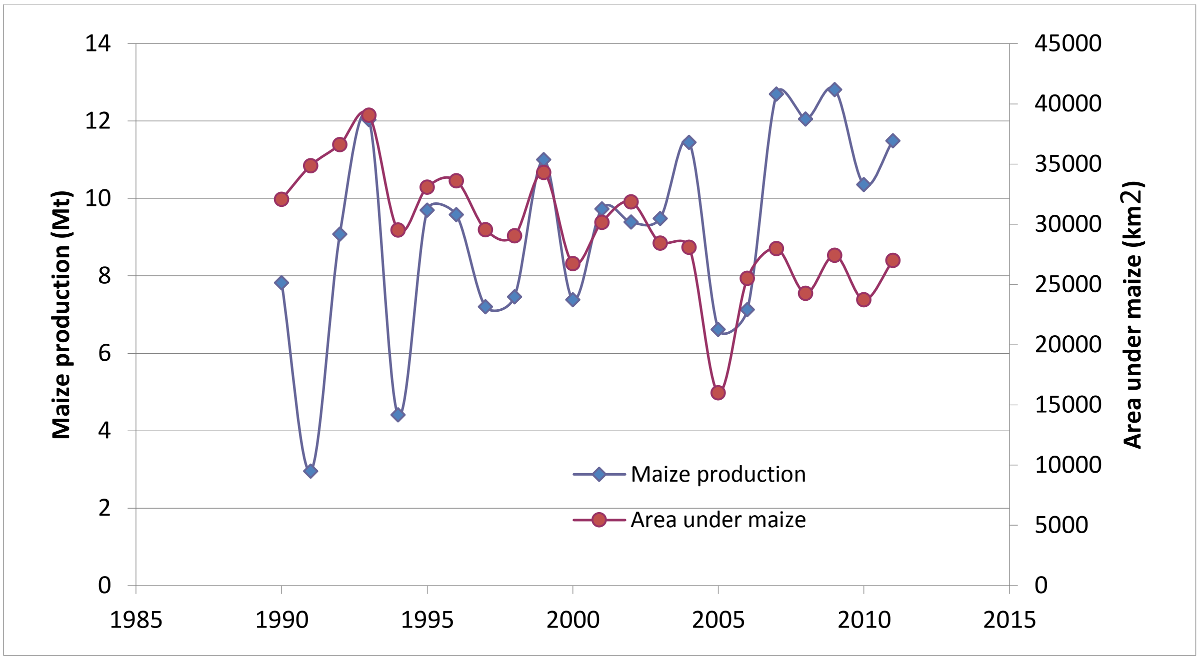

Figure 2.2 Trends in maize production in South Africa

Source: South African Grain Information System (SAGIS) (2016)

Figure 2.2 shows that between 1990 and 2010, maize yields increased from an average of 2.4 t.ha^{-1} to 4.4 t.ha^{-1}. The National Department of Agriculture (DAFF) (2014) reported a decrease in yield from 4.96 t.ha^{-1} in the 2008/2009 production season to 4.21 t.ha^{-1} in 2012/2013, as shown in Table 2.1. BFAP (2016) and GrainSA (2017) reported a national average yield of 4.0 t.ha^{-1} for the 2016/2017 marketing year.

Table 2.1 Plantings, production and yield of commercial maize from 2008/2009 to 2012/2013 seasons

Season	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**	**2012/2013**
Planting (ha)	2 427 500	2 742 400	2 372 300	2 699 200	2 781 200
Production (t)	12 050 000	12 815 000	10 360 000	12 120 656	11 722 556
Yield (t.ha^{-1})	4.96	4.67	4.37	4.49	4.21

Source: DAFF (2014)

The Mpumalanga, Free State and North-West provinces contribute 85 % of the total national maize production in the country (DAFF, 2011).

2.1.3.2 Market trends

The overall value of production in agriculture is determined by the quantity of produce and prices received by the farmers. DAFF (2013) reported maize as the largest contributor towards the gross value of field crops, with a value of R23 814 million for the 2012/2013 season. The maize market in SA has, essentially, been an open one since the deregulation of the agricultural market in 1996 (Sihlobo, 2016). The prices are determined by several factors, which include:

- Exchange rates;
- Local production (dependent on production area and climate conditions);
- Local consumption;
- International maize prices;
- Domestic and international stock levels; and
- Production levels in the SADEC region.

The average producer prices of maize from 2008/2009 to 2012/2013 seasons are given in Table 2.2.

Table 2.2 Average producer prices of maize from 2008/2009 to 2012/2013

Season	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**	**2012/2013**
Producer price	**R/ton**				
	1 304.94	1 004.84	1 531.06	1 970.20	1 976.45

Source: DAFF (2013)

Kapuya and Sihlobo (2015) reported that the price of maize increased to R2 168/ton due to high export demand in 2014, and by a further R830/ton to R2 998/ton between the end of January and mid-February 2015 after the prices were pushed up due to emerging fears of drought. The report also recorded a price of R3 011/ton in August 2015, as shown in Figure 2.3.

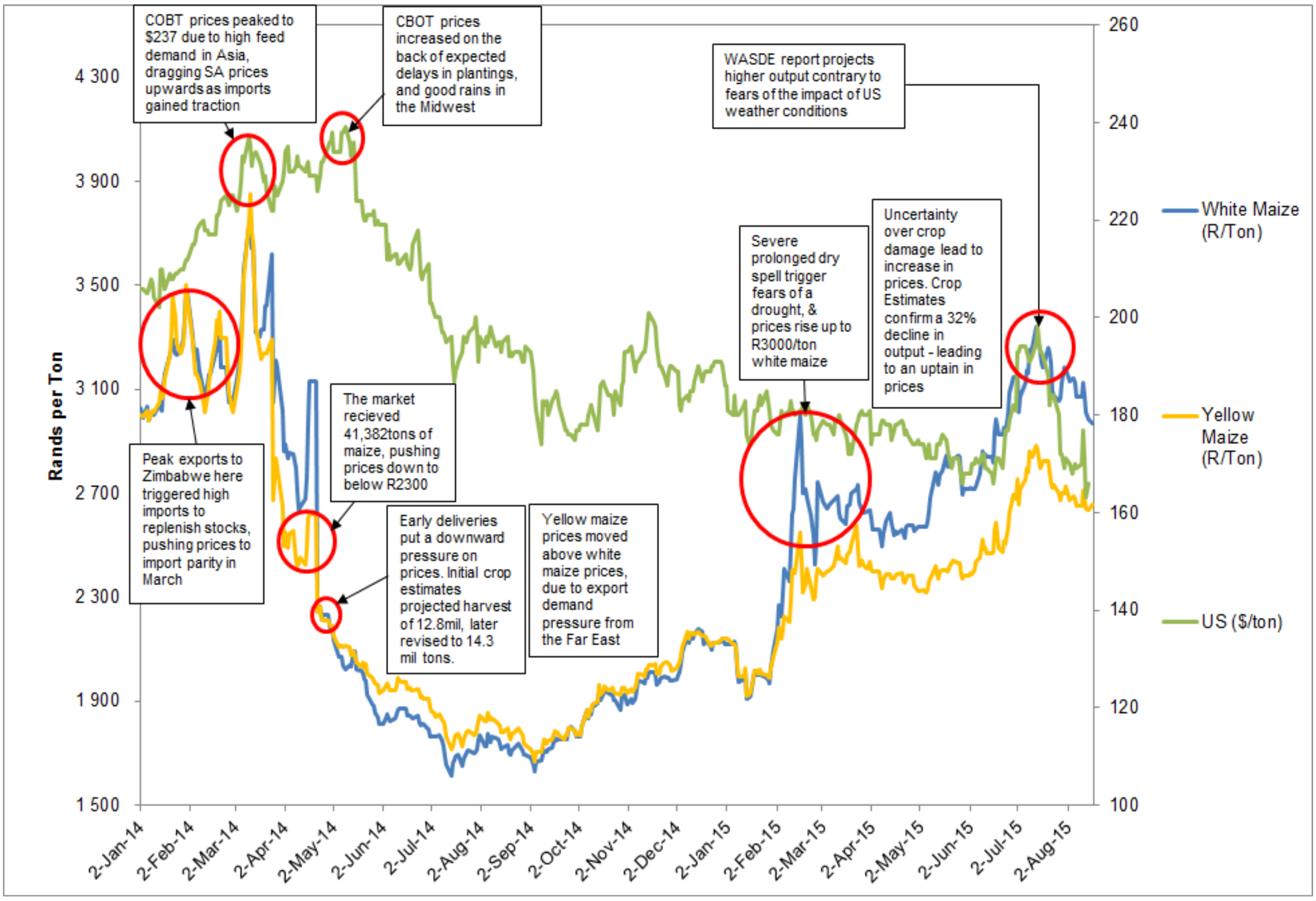

Figure 2.3 Market trends in domestic and international maize production

Source: Kapuya and Sihlobo (2015)

The following table shows market-to-market prices of maize for the period March 2016 to March 2017.

Table 2.3 Market-to-market prices for maize in South Africa

Commodity	**Mar-16**	**Apr-16**	**May-16**	**Jun-16**	**Jul-16**	**Sep-16**	**Dec-16**	**Mar-17**
	R/ton							
White maize	5 035	4 720	4 408	4 450	4 482	4 553	4 600	4 370
Yellow maize	3 458	3 121	3 134	3 167	3 208	3 260	3 308	3 298
Average	4 247	3 921	3 771	3 809	3 845	3 907	3 954	3 834

Source: Swarts (2016)

2.1.3.3 Main product and co-products

The maize plant has a wide range of uses, because of its relatively low price and worldwide distribution. The main product in maize production is its grain, which is used for human consumption in various forms. Co-products include the stover and cobs which are mainly used for animal feed and bedding. There is also a growing interest in using maize for the production of bio-fuels, such as ethanol.

Grain for human consumption

Maize in its green form can be consumed directly by humans. The ear (kernels on the cob) can be boiled or roasted to produce creamy palatable grains. Maize grains can also be canned as ready-to-eat food articles when the crop is out of season. Dry maize grains can be consumed as a snack, i.e. pop-corn. The grain can be milled into maize meal for preparation of porridges of various forms and into maize flour. Breakfast cereals, like corn-flakes, are prepared from cooked, dried, rolled and toasted grains.

Grain and stover as livestock feed

Maize green forage, consisting of the stalks, ears and leaves, can be used as an energy feed for livestock. Green fodder is provided to livestock in harsh conditions and when forage is scarce, through grazing whole maize plants (Potter, 2012 and Newport, 2006). Although their nutritive value is low, maize cobs are carriers for vitamins and antibiotics in animal feed (Evers *et al*., 1994 and Jansen, 2012). The maize grain is used as a source of energy and is considered a major feed grain and standard component of livestock diet. Both white and yellow maize can be fed to livestock as hay or silage. Yellow maize contributes significantly to the production of white and red meats and dairy products. Heuzé and Tran (2016) stated that “Maize grain is fed as dry maize grain (less than 15% moisture) or high-moisture maize grain (22 to 28% moisture)”.

Grain and stover for industrial uses

Maize grain contains starch that is used in making confectionery products and other products like noodles. An all-purpose culinary oil can be extracted from maize seeds. Maize grain contains a high level of fructose and is processed into maize syrup which is often used as a sweetener. Maize silk - stigmas from the female flowers, can be used as herbal supplement. Ethanol obtained from maize can be used as bio-fuel. Maize stover is often used as a cheap source energy for home-heating furnaces. Levulinic acid is derived from maize and used as a chemical ingredient in antifreeze (Alipour and Omidvarborna, 2016), with the prospect of replacing toxic petroleum-based ingredients currently used. Maize stover can be used in the production of fabrics and plastics.

2.1.4 Energy potential

Crop residue used in bioenergy production must have sufficient energy content. Energy potential of feedstock can be defined as energy per unit volume or weight – energy density (Zych, 2008). The volume of biomass required to be harvested, transported, stored and utilized in an energy production process is affected by the volumetric energy density of the feedstock (McKendry, 2002). One can therefore deduce that less volume of biomass would be required to produce a given amount of energy if the energy density is high. Maize cobs have similar energy density to other feedstocks which have been globally accepted for utilization in energy production. Table 2.4 compares the volumetric and mass energy densities of several feedstocks.

Table 2.4 Energy densities of several feedstocks on dry basis

Fuel	Maize cobs	Maize Stover	Switchgrass	Wood Pallets	Bituminous Coal	Fuel Oil
Energy content (MJ/kg)	18.25 – 19.18	17	18	19	25.5	43.5
Energy content (MJ/m^3)	4 960 – 5 210	2 550	2 500	12 400	23 300	38 600
Reference	*Clark and Lathrop, 1953*		*Foley, 1978*	*Powder and Bulk.com, 2008*		*McLaughlin, et al., 1996*

The energy density of maize cobs is given in Table 2.4 in MJ/kg of dry matter; the moisture content should be taken into consideration as maize cobs are not harvested, stored or used in a moisture free condition. Murphy and Masters (1978) and Chan *et al*. (2001) stated that the energy content of raw wood at 20% moisture content is around 15 MJ/kg. According to Ashter (2017) one of the advantages of biomass densification is that the process increases energy density while overcoming handling difficulties. The table above shows that maize cobs are sufficiently dense and don't require densification as wood pallets do in the process of palletisation.

The energy potential of crop residues has previously been evaluated by multiplying the quantity of the residue and the calorific value. However, the diverted quantity of residue was not taken into account as a factor (Reese, 2011). The activities that occur between harvesting and generation of power from crop residue have a direct effect on the energy potential. According to McKendry (2002) the available energy potential can be defined as a product of the calorific value of a certain type of residue and the available residue from the crop for power generation.

Bioelectricity power plants around the world have a limited potential of less than 200 MW due to the fact that biomass residue cannot be collected at 100 % because of geographic factors (Zych, 2008). Increased capacity would require large quantity of resources and high costs in feedstock logistics planning.

2.2 Electricity production

2.2.1 History of electricity demand in South Africa

Energy played a vital role in the building of the economy of South Africa. The demand for energy in the mining industry drove electricity supply in the early twentieth century (Winkler *et al*, 2006). The Electricity Supply Commission (ESCOM) was established as a relatively autonomous entity in 1923 in line with the 1922 Electricity Act (Koen, 2012). The company was known as the Elektrisiteit Voorseinings Kommissie (EVKOM) and later became Eskom when the two acronyms were combined in 1986.

Large power station projects were carried out to meet an assumed rapidly growing demand. Eskom (2000) reported that between the 1980s and 1990s, the national utility was left with an excess capacity. Figure 3.1 below shows the excess capacity which is the difference between total licensed capacity and peak demand.

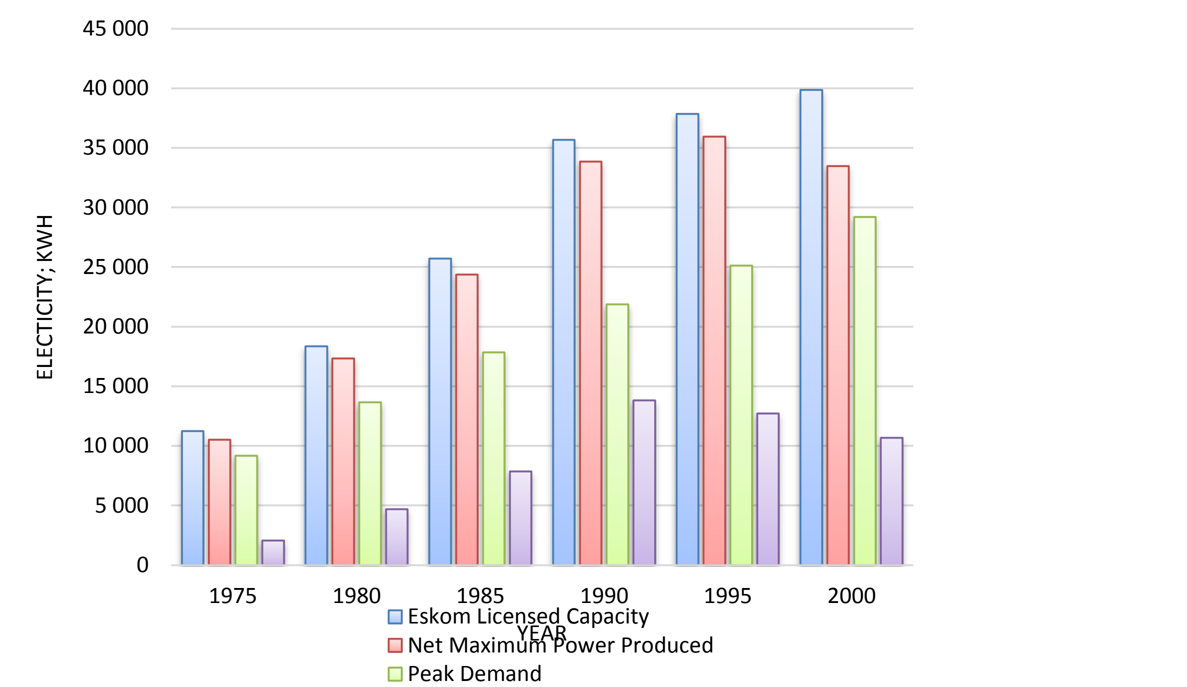

Figure 2.4 Eskom licensed capacity and peak demand

Source: Eskom (2000)

Plans for further expansion were scaled down in 1985 after mines and other industries were hit with foreign loan cutoffs. In the early 1990s only about 40 % of the country had access to electricity, but the new government in 1994 prioritized the supply of electricity to rural areas and all South African citizens. The excess capacity was exhausted in the early 2000s.

In history, energy demand has been dominated by energy intensive industries which rely on the accessibility of low-cost coal and electricity. According to SANEA (2008), in the early 2000's, final demand was dominated by the transport and industry sectors, as shown in Figure 2.5 below.

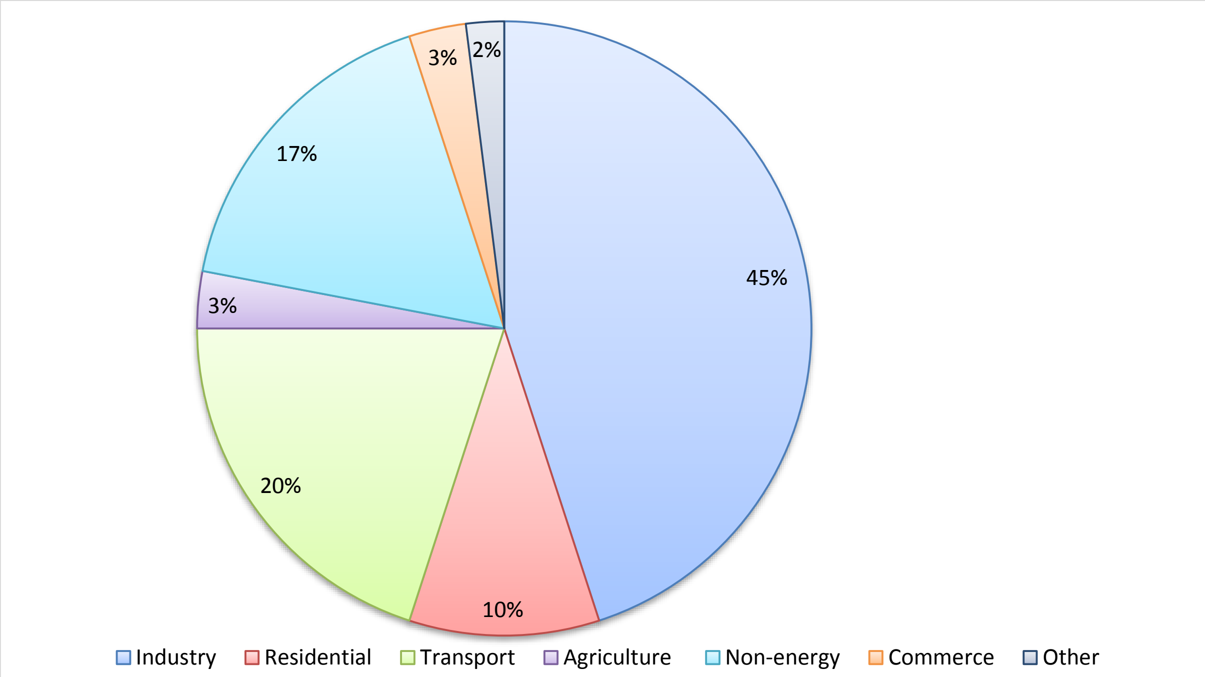

Figure 2.5 Eskom licensed capacity and peak demand

Source: SANEA (2008)

Various literature show that industrial demand continued to be the major source of growth across all energy carriers. Electricity has played a vital role in the SA economy as the electricity intensive industries such as mining and manufacturing are some of the largest contributor to exports and economic growth. Trollip (1996), DME (2000) and Berger (2000) reported that these industries took up more than 60 % of the country's electricity sales.

The residential sector was also a large contributor to growth in electricity demand between the late 1990's and the year 2000 (Davis, 1998 and NER, 2000). The post-1994 government drafted policy aimed at connecting 2.5 million households by 1999 (ANC, 1994). This resulted in an increase of the overall electrification rate to 66 % in 2001 (NER, 2001) and a grid connection of a further 338 572 households, 49 clinics and 974 schools in the year 2002, as reported by DME (2003).

2.2.2 Current state of electricity demand

South Africa's demand for electricity is increasing quickly; however, the current generation capacity is not enough to meet the demand. Access to electricity for residential areas increased from 30 % in 1994 to 73 % in 2005, and only about 46 % of the rural community is not connected to the main grid (CSIR, 2009). According to Inglesi and Pouris (2010), electricity demand increased by 50 % between 1994 and 2007 due to the 2001 Free Basic Electricity Policy.

Since 2007, Eskom has experienced a capacity problem, citing the government's delayed decision to fund the building of new power stations. This resulted in power cuts which began in 2008 and, consequently, a decrease in the rate of economic growth from 5.4 % in the last quarter of 2007 to 1.57 % in the first quarter of 2008 (Moodley, 2010). In February 2009, the former CEO of Eskom, Mr Maroga, reported a mismatch between electricity supply and demand during a presentation to the Parliament.

Eskom currently generates about 95 % of the country's electricity, with 90 % of it being derived from coal (Buckley and Nicholas, 2017). A portion of the electricity generated is used in power stations and imported to neighbouring countries. The remaining bulk of the electricity produced is consumed by government, industrial, residential and business sectors. The graph below shows South Africa's electricity consumption from 2000 to 2014. The country's economy continues to be under strain due to the energy crisis. Hedden (2015) reported that SA experienced power cuts, known as load shedding, every third day (on average) during the first four months of 2015.

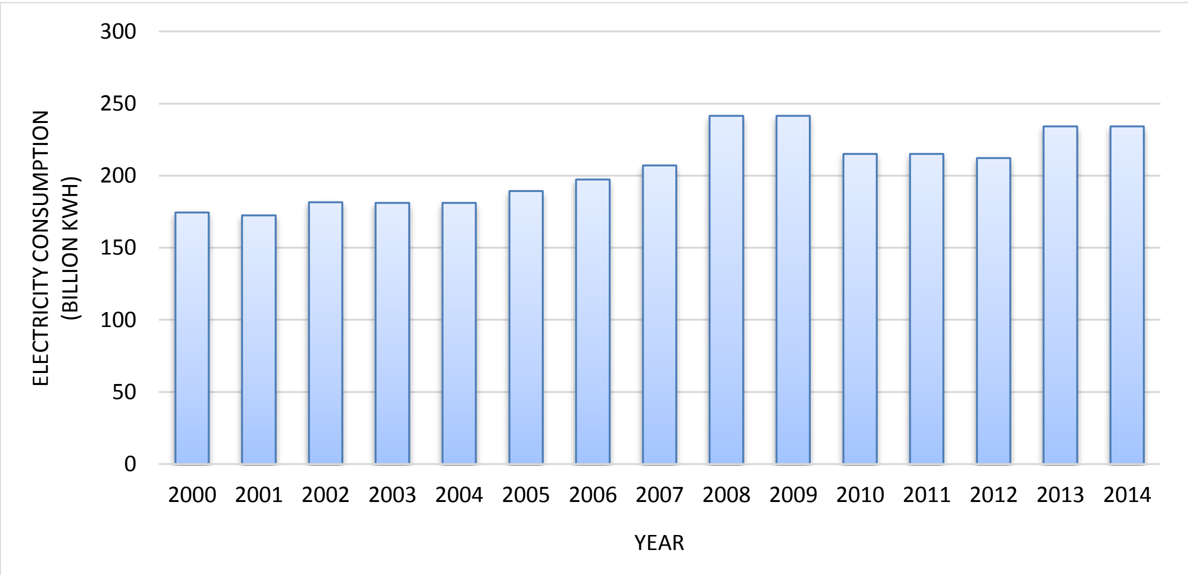

Figure 2.6 South Africa's electricity consumption between 2000 and 2014

Source: CIA World Fact Book (2016)

2.2.3 Outlook for the future of electricity demand

The supply of electricity is essential for the augmentation of economic and social development and the improvement of the livelihood of the South African population. In order to meet the country's future electricity needs and reduce GHG emissions, the DoE has set certain goals on extending electricity supply technologies to include nuclear, biomass and renewable resources. The National Development Plan (NDP) predicts that over 95 % of the population will have access to electricity by 2030 (SA Government, 2016).

Some of the key priorities of the NDP (2010) are to procure 20 000 MW of renewable electricity by 2030 and decommission about 11 000 MW of aging coal-fired power stations. Local coal supply security is under threat for some existing coal fired power stations as coal mines are unwilling to sign long-term contracts with Eskom due to high prospects of return through exports.

2.2.4 Overview of electricity generation methods

Electricity generation is defined as the process of producing electrical power from other sources of primary energy. Electricity was discovered by Michael Faraday and first generated by the movement of a disc of copper or a loop of wire between two poles of a magnet (Beléndez, 2015). Coal power and hydroelectric power plants became the first to be constructed (Termuehlen and Emsperger, 2003).

2.2.4.1 Conventional system - Coal power

In this technique of electricity generation (shown in the picture below), coal is first pulverized or milled into a fine powder in order to increase the surface area and the rate of combustion. The coal is then blown into the combustion chamber of a boiler, where high temperature is used to burn it. This is known as the pulverized coal combustion (PCC) system. Hot gases and heat energy are introduced. This is then used to convert water, in tubes that line the boiler, into superheated steam. The steam is then used to turn a turbine. The turbine turns a rotor (copper wire) inside a stator; these make up the generator. The generator then converts this mechanical energy into an electric current, which is distributed to consumers via power lines.

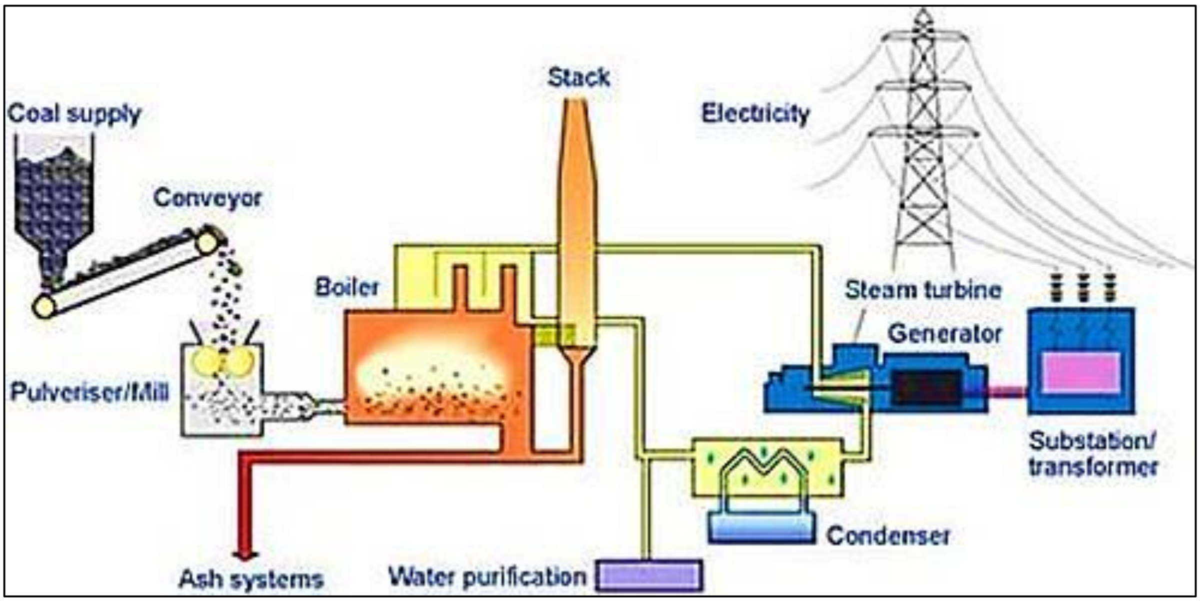

Figure 2.7 The process of generating electricity form coal
Source: WCI (2010)

Coal power is used to the generate electricity that powers industrial and manufacturing plants as well as households. It is used because it is an affordable source of energy and coal is abundant even though it is non-renewable. The advantages and disadvantages of using coal energy to generate electricity are outlined below.

Advantages of using coal to generate electricity:

- The price of coal is more stable compared to other fuel sources, which make coal energy more affordable.
- Coal is easy to burn and produces high energy upon combustion.
- Coal is abundant, with very large reserves around the world.
- Coal power is a reliable source of energy.

Disadvantages of using coal to generate electricity:

- The burning of coal is not environmentally friendly as it produces harmful byproducts and gas emissions like carbon dioxide, sulphur dioxide and nitrogen oxide that cause acid rains, harmful to humans.
- Coal power leads to global warming and climate change due to the large amount of carbon dioxide produced.
- Coal energy is a non-renewable source of energy and coal is depleting rapidly because of its massive use.

- Mining of coal results in the displacement of humans and destruction of the environment. Places near coal mines are unsafe because the land could cave in.
- Waste products that contain harmful substance and can no longer be reused are generated from coal fired power stations and contribute to disposal problems.

2.2.4.2 Renewable energy – Biomass

Renewable energy refers to all types of energy that are derived from natural resources that are continuously replenished and cannot be exhausted. These sources include sunlight, wind, tides, geothermal heat, water and various types of biomass. Biomass is a sustainable and renewable source of energy that is derived from organic materials to create electricity or other forms of power. Types of biomass materials that can be used as fuel are included in Table 2.5.

Table 2.5 Biomass resources classified according to the supply sector

Supply Type	Sector	Example
Forestry	Dedicated forestry	Short rotation plantations such as Willow, poplar, eucalyptus
	Forestry by-products	Wood blocks and chips
Agriculture	Agricultural residues	Straw, prunings from vineyards and fruit trees
	Livestock waste	Dry and wet manure
	Dry lignocellulosic energy crops	Herbaceous crops such as reed canary grass, giant reed
	Oil, sugar and starch energy crops	Sugarcane, sweet sorghum, rape seed, sunflower, wheat, maize
Industry	Industrial residues	Industrial waste wood, sawdust from sawmills, fibrous waste from paper industries
Waste	Dry lignocellulosic	Parks and garden residues such as grass, prunings
	Contaminated waste	Municipal waste, biodegradable landfill waste, landfill gas, sewage sludge, demolition wood

The characteristics of the ideal crop for generation of energy include high yield, low cost and low nutrient requirements. An ideal energy crop is also produced with low energy input and is composed of minimal contaminants (McKendry, 2002). Other characteristics include climatic and soil conditions, drought resistance (in water scare areas), pest resistance and fertiliser requirements. The important properties in the conversion of biomass into energy relate to calorific value, intrinsic and extrinsic moisture content, ash/residue content, cellulose/lignin value, alkali metal content as well as proportions of fixed carbon and volatiles.

It is clear that the harvest and mass-production of biomass fuel products provides a new source of power, for use in various applications from engines to power plants. In many ways, biomass is a new source of power. The advantages and disadvantages of generating energy form biomass are given below.

Advantages of using biomass to generate electricity

- No Harmful Emissions: The use of fossil fuels releases carbon dioxide to the atmosphere and, as a result, increases the effects of greenhouse gases. Although the burning of biomass releases some carbon dioxide, the CO_2 released is captured for its own growth. The use of biomass in energy production reduces the greenhouse gas emissions to virtually none.
- Renewable Energy Incentives: Because of the relatively clean use of biomass energy, its use in commercial business is incentivized by most governments globally. This is both beneficial to the environment and business.
- Abundant and Renewable: Since they come from living sources, and life is cyclical; biomass products potentially never run out. Biomass energy will exist for as long as there are means of turning components of living organisms and their waste into energy.
- Reduce Dependency on Fossil Fuels: Renewable energy has developed into a reliable source of energy and has significantly reduced the entire world's dependency on fossil fuels.
- Can be used to Create Different Products: Different forms of organic matter can be used to create different types of fuel, making biomass energy versatile. Ethanol and similar fuels can be made from maize and other crops.

Disadvantages of using biomass to generate electricity

- Expensive: Extraction and storage of different types of biomass can be very expensive. This is also true for the conversion into energy, compared to fossil fuels.
- Consume More Fuel: Using crop products to generate energy is less efficient than the conventional fossil fuels, as it requires more fuel to do the same job as the conventional methods.
- Require More Land: Since it requires more fuel to produce the required amount of energy as it would with conventional fossil fuel, more land is required to produce energy crops. The combustion of biomass products releases gases like methane into the environment, it therefore should, be produced in areas which are far from residential homes. This again necessitates the availability of more land.

Biomass conversion

Biomass can be converted into transport fuel, chemical feedstock or electrical/heat energy. This study is interested in the generation of electricity from biomass. Discussed in this study is the process of converting biomass feedstocks into energy which is then used to generate electricity and/or heat. Biomass conversion technologies include anaerobic digesters for wastewater or animal waste, direct-fired boiler systems for woody biomass and gasification for dry biomass such as agricultural residue or wood.

<u>Collection method</u>

The amount of biomass feedstock that can be collected for conversion at a given time is dependent on multiple factors. For energy crops and agricultural residues, it is important to consider the efficiency of the collection method, the type and sequence of collection operations, tillage and management practices, and conservational restrictions such as the need to maintain soil carbon levels and soil productivity, and to control soil erosion. Agricultural residues are usually collected using the same mechanism that is used to collect hay. Maize cobs and stover (leaves and stalks) are collected in a collection wagon hauled behind the combine harvester. Some of these collection wagons are able to separate cobs from other maize stover. Wheat stalks are baled up by a baling machine and then loaded into a truck (McKendry, 2002).

Biomass preparation

Biomass feedstocks are prepared, stored and transported to the energy conversion process before they can be used to generate electricity. This is done in the preparation yard which is divided into four main sections, namely, receiving, processing, buffer storage fuel metering (EPA, 2007). Small facilities have preparation yards that require a lot of manual labour, while larger facilities use automated systems. Biomass is delivered to the energy conversion facility by trucks. The choice of truck depends on the amount of biomass feedstock as well the equipment available for unloading. Dump trucks and live-bottom semi-trailer vans are able to unload themselves directly onto the storage piles, while standard semi-trailer vans require truck dumpers to unload.

During processing, the biomass is treated before the energy conversion process. The process includes separation, sizing, removal of foreign and incombustible materials, and size reduction methods. This system can be manual – requires a front-end loader, or automated – conveys the required quantity of biomass to be used in the conversion process. The sizing equipment sizes the biomass material to meet boiler specifications. The sized material is then conveyed into a silo to be stored until they are needed.

If the biomass requires drying, especially if gasification will be used, this occurs immediately after the sizing. The energy efficiency of the conversion process is increased when the moisture content of the biomass feedstock is low (EPA, 2007). A silo serves as storage buffer. The size of the buffer depends on the fuel consumption rate of the boiler. The material is moved to collector conveyors by the live bottom of the silo. The fuel metering system ensures that the required quantity of biomass is delivered to energy conversion process. Metering of the biomass is done as the material is discharged from the collecting conveyor. The boiler control room controls the rate of metering.

Conversion technologies

There are three main types of biomass conversion technologies for electricity generation; these are combustion, anaerobic digestion and gasification. Biomass electricity generation systems are usually below 50 MW in size, much smaller than coal-fired power stations which are between 100 to 1 000 MW (IEA, 2007).

Combustion is currently the most prominent biomass conversion technology in the world. In this process, air is used to breakdown biogenic material and release thermal gases; these are used to run boilers for the production of superheated steam which is used to drive a turbine generator for energy production (Zych, 2008). The exhausted steam generated in this process can be utilized for other applications. This makes the technology suitable for operation of combined heat and power (CHP) facilities.

The technology ensures that a lot of the heat generated for the demand by consumers is captured while minimising heat lost to the environment. This process can achieve a net power cycle efficiency of 23 to 25 % (IRENA, 2012; IEA, 2007). Biomass can be co-fired with coal in this process. This involves a substitution of a portion of the coal in a coal power plant boiler. When compared to the coal replaced by the introduced biomass, SO_2, NO_x and other emissions are reduced.

According to EPRI (2010), anaerobic digestion occurs in almost any biological material that is decomposing and is favoured by wet, warm and airless conditions. This results in biogas consisting mainly of carbon dioxide (CO_2) and methane. The biogas is cleaned up and then used in fuel cells, Stirling engines, internal combustion engines and turbines or upgraded to biomethane for distribution.

Gasification is a biomass thermochemical conversion process that is used to acquire energy from solid matter in gaseous form (Ravindranath, 1993). The process begins with a thermal decomposition reaction in the absence of oxygen, then air or oxygen is introduced to convert organic matter into combustible gas and, at the same time, translating the calorific value of the biomass into an energy carrier (Ravindranath, 1995; Tripathi *et al*, 1997 and Purohit, 2009). The types of gasifiers used are fluidized bed, fixed bed and entrained flow gasifiers. Syngas consists of CO_2, carbon monoxide, hydrogen, tar, char and water. This is used in fuel cells, gas turbines, combustion engines or micro-turbines. Higher electrical efficiency is achieved when the syngas is used in fuel cells and turbines, than in steam turbines. Figure 2.9 below shows how the gasification is used to generate electricity.

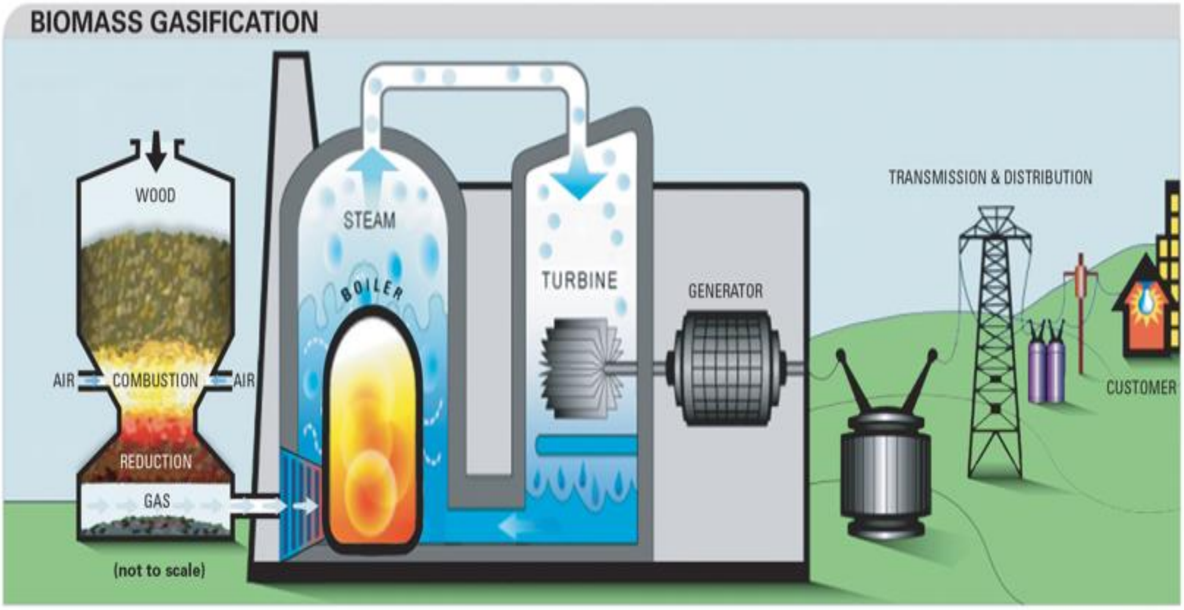

Figure 2.8 The biomass gasification process
Source: Tripathi *et al* (1997)

The conversion technologies discussed above have different feed size, moisture content and capacity range specifications (as shown in Table 2.6 below).

Table 2.6 Summary of biomass conversion technologies for power generation

Biomass conversion technology	Common fuel types	Feed size	Moisture content	Capacity range
Stoker gate, underfire stoker boilers	Sawdust, bark, hog fuel, end cuts, sawdust, shavings	6.35 – 50 mm	10 – 50 %	4 to 300 MW
Fluidized bed boiler	Woody residue, peat, wide variety of fuels	< 50 mm	< 60 %	Up to 300 MW
Fixed bed gasifier	Chipped wood or hog fuel, rice hulls, shells, sewage sludge	6.35 – 102 mm	< 20 %	Up to 50 MW
Fluidized bed gasifier	Most wood and agricultural residues	6.35 – 50 mm	15 – 30 %	Up to 25 MW

2.2.5 Energy production from maize cobs

Maize cobs are a suitable feedstock for production of energy using various methods due to their physical and chemical properties. Maize cobs contain 32.3 – 45.6 % cellulose and 39.8 % hemicellulose (mostly comprised of pentosan and up to 13.9 % lignin) (Clark and Lathrop, 1953; Foley, 1978). Gasification and combustion are thermochemical conversion technologies that are able to use the molecular structure of the cellulose, hemicellulose and lignin in the maize cob to produce synthetic gas and/or heat energy (Zych, 2008). Suberu *et al* (2012) stated that energy production using biomass is best accomplished when power is generated and applied to consumers close to the area – by distributed technology. Maize cobs are crop residues which are commonly treated as dry biomass for the generation of energy through gasification and combustion.

Global interests in power generation from renewable energy resources have grown mainly due to the increasing efforts to prevent harmful environmental activities arising from energy consumption. More than 10 % of the world's primary energy consumption is being derived from biomass resources (Heinimö and Junginger, 2009). Land use (and agriculture) can be used for cultivating conventional crops for production of bioenergy. Bioenergy is the energy produced through the use of physical and chemical properties of biomass. Biomass materials include dedicated crops, forestry wastes, aquatic vegetation, municipal wastes and agricultural residue from crops such as rape, wheat, maize, etc.

The selection of biomass feedstock depends on energy density, production rate, moisture content, particle size, chemical composition and sustainable production of the feedstock (Williams, 2016). The use of biomass for energy production could ultimately displace large amounts of fossil based fuels and in turn reduce the level of GHG emissions. When energy is produced from biomass, the carbon dioxide emitted during the combustion process enters the atmosphere and is reused by living plants. Maize cobs have been used as fuel for direct combustion in cooking and heating on a small scale, however research has shown that their use for large scale energy production is a relatively new concept. In countries like Nigeria, where the energy situation is in crisis, maize cobs are one of the main bio-energy resources. The annual maize grain production system results in about 204 million dry metric tons of maize residue being returned to the ground as waste by-product (Perlack *et al*, 2005).

2.3 Life cycle assessment

2.3.1 Definition

Life Cycle Assessment is defined in ISO 14040:2006 as the "compilation and evaluation of the inputs and outputs and potential environmental impacts of a product system throughout its life cycle". The United States Environmental Protection Agency defines LCA as a method used to evaluate the environmental aspects and potential impacts related to a product system by putting together an inventory of the applicable energy and material inputs and environmental releases, evaluating the probable environmental impacts associated with the identified inputs and outputs, and finally, translating the results as an aid of informed decision making (SAIC, 2006).

Life Cycle Assessment is therefore a tool used to analyse the environmental implications of products at all stages of their life cycles. The environmental implications include all kinds of impacts on the environment, including land use, extraction of various resources and emissions of gases and other substances (Williams, 2009). LCA studies account for environmental impacts associated with physical goods and services at operational and strategic levels.

2.3.2 Development of LCA

The history of LCA of consumer products dates back to the 1960s and 1970s, when the viability of one product was compared against another (Guinée *et al*, 2010). For many of the products, the environmental burden is due to their production, transportation and/or disposal and not the use of the products. During this period, studies were more inclined toward evaluation of resource and energy efficiency, pollution control and solid waste management, as these were issues of public concern (Assies, 1992).

From 1975 through the 1980s, environmental concerns shifted to issues of hazardous and household waste management. At the same time, life cycle inventory analysis was being conducted and methodology was being improved (SAIC, 2006). The European Commission standardized pollution regulations and developed ways of monitoring the use of raw materials and energy and the generation of solid waste (Guinée *et al*, 2010).

In 1989, the Society of Environmental Toxicology and Chemistry (SETAC) became the first international organization to coordinate the development of LCA (Guinée *et al*, 2002). SETAC developed a technical structure for LCA that was internationally accepted and became the precursor of activities performed by the International Organization of Standards (ISO) as well as improve the quality of their work. In 1994 ISO developed the 14000 series of standards aiming at producing the first complete series of LCA standards. These standards address the organizational and technical aspects of LCA. The LCA of maize cobs for energy production in this research project will be base extensively on standards developed by ISO, particularly, the ISO 14000:2006.

2.3.3 Main characteristics of LCA

LCA is mostly qualitative on nature, but can also have quantitative attributes which should be taken into account, where possible, in order to fully demonstrate the environmental impacts involved. LCA is a holistic analysis that involves a well-rounded approach. The main applications of LCA according to Silva *et al* (2015) are in:

- Selecting between a range of comparable products;
- Designing new products;
- Comparing improvement options of a particular product; and
- Analysing the foundations of problems relating to a specific product.

The implementation of an LCA project depends on the intended use of the results.

2.3.3.1 Benefits of conducting an LCA

LCA can be used, along with other studies, to influence a decision with regards to choosing a process or product that results in the least environmental impact. Data obtained in a LCA study identifies the transfer of environmental impacts from one channel to another or from one life cycle stage to another. The study allows a decision maker to investigate an entire product system, and as a result, avoid shifting of environmental problems from place to place (Guinée *et al*, 2002).

2.3.3.2 Limitations of LCA

Life Cycle Assessment does not focus on localized impacts. It does not provide a fundamental structure for a complete local assessment. The approach of an LCA is not of a dynamic character but is rather a steady-state method (Guldbrandson and Bergmark, 2010). LCA focuses on physical attributes of industrial activities and economic processes and not secondary effects on technological development or market structures. LCA regards environmental and economic processes as linear (Singh *et al*, 2013).

Environmental aspects of products are the main focus of LCA studies; the structure does not address social, economic and other product characteristics. The environmental impacts are not quantified in space or time and are associated with a subjectively defined functional unit (Doka *et al*, 2000). Data used in LCA studies are often obsolete, incomparable or of unknown quality. Data is not always available. LCA is only and analytical tool, it cannot replace the entire decision making process, it can only provide information to support a decision (Guinée *et al*, 2002).

2.3.4 LCA Methodological framework

Agriculture is a very broad field with the capability of producing a wide range of products which are important to society. The struggle for natural resources is bound to increase due to the increase in global population. This will impose pressure on agriculture, particularly the production of fibre, food, energy and high-value by-products. The use of maize cobs, and other agricultural wastes, for the production of energy is a good example of the role of agriculture in society.

The nature of agriculture is complex with multiple impacts on the environment. The use of LCA will help shed light on these complexities and assess the system's environmental performance. The LCA methodological framework consists of four phases, namely;

- Goal and scope definition;
- Life Cycle Inventory (LCI);
- Life Cycle Impact Assessment (LCIA); and
- Interpretation.

2.3.4.1 Goal and scope definition

In this step, the product system is designed in detail by establishing the context of the study and identifying the environmental impacts to be reviewed.

Goal

To specify how the rest of the analysis will be conducted, it is important to determine the goal of the LCA. According to ISO 14040:2006, this consists of four components, namely; intended application, reason for the LCA study, intended audience and stating if the results will be used for comparison. The goal of the study helps to derive quality control requirements. The interpretation and evaluation is done in close relation to the goal of the study. It is therefore important to ensure that the goal is clearly defined from the beginning.

<u>Intended application</u>

The intended application(s) of the LCA should be stated in an unambiguous and precise way (European Commission, 2010). Several applications may be addressed by a single study.

<u>Reasons for carrying out the study</u>

The goal definition should identify the decision context, name the drivers and motivators and explain the reasons for carrying out the study (European Commission, 2010). The decision context helps determine the LCI approach and modelling framework to be used. It also has a direct link to the scope of the study, inventory data collection and modelling, impact assessment results and interpretation of results. The reasons for the study give an indication of the data quality requirements.

<u>Target audience</u>

The intended audience for the study should be identified by the goal definition. The relevant technical level and form of reporting as well as critical review needs can be identified by the defined audience.

Comparison

It should be stated explicitly if the LCA study will include comparisons to results of other studies. The "comparison" refers to comparison of two systems and not within a single system. ISO 14044:2006 states that a life cycle study that does not include LCIA and interpretation shall not be used for comparative assertions.

Scope

The exact product or system to be analysed is identified and defined in detail during scope definition. This is done in conjunction with the goal definition. The main purpose of scope definition is to determine what is required in methodology, reporting, quality and review according to the defined goal. The following aspects are to be addressed by the scope of the study:

System boundary

The system boundary defines what is to be addressed and what is not in the LCA. The boundary needs to be in line with the defined goal. According to Tillman *et al.* (1994), system boundaries must be specified in the following dimensions:

- Boundaries between the life cycle of the product system under study and related life cycles of other products.
- Boundaries between the technological system and nature.
- Boundaries between production and production of capital goods.
- Delimitations of the geographical area and time horizon considered.

For agricultural systems, there is a large amount of material processing of inputs and processing material beyond the farm gate, it is for this reason that defining the system boundary is important. LCAs taken beyond the farm gate may include postharvest handling, transportation and the processing of food. The processing of agricultural products beyond the farm gate may complicate the overall analysis of the results (Ruviaro *et al.*, 2012). Correctly defining the system boundary in conjunction with the goal of the study is therefore very important.

System's function and functional unit

The system's function and functional unit are key aspects of LCA. The functional unit quantifies the function of the study (e.g. function: electricity generation, functional unit: 1 kWh). The audience that the LCA is meant to address and the goal of the study affect the use of a functional unit. The definition of the functional unit also affects the results of the study (Charles *et al*, 2006; Hayashi, 2013 and Haas *et al*, 2000).

2.3.4.2 Life cycle inventory

This step identifies and quantifies material, water and energy use as well as environmental emissions. The process can also be used as a tool to compare the environmental impacts and to find improvement opportunities for processes or products. This stage involves the development of a flow process diagram, data collection, allocation method and LCI modelling. Approximations and assumptions are made when data is not directly available.

Data

The most common limitations associated with LCA studies are data gaps and scarcity of data. Canals *et al* (2011) suggest the use of "known, verified data with similar properties to those of the case under study" (known as proxy data sets) or "new derived data by modifying existing, known data considering the case-specific characteristics" (extrapolated data sets), in order to address these limitations. These approaches have their own advantages and disadvantages.

When considering the budget and time constraints of LCA studies, the proxy approach is a quick and easy solution. However, the uncertainty is high as available data do not usually reflect the system currently under study and they are not a good approximation of reality (Koukouna, 2014). The extrapolation approach requires extensive expert knowledge, but it is more effective in reducing data gaps (Koukouna, 2014).

Allocation methods

For a multi-product process, the allocation procedure is a critical issue. To solve the multi-functionality issue, allocation methods that are a function of the co-functions (e.g. mass, market price, energy content and element content, etc.) are used (ILCD, 2010). Allocation is defined in ISO 14044:2006 as “partitioning the input and/or output flows of a process to the product system under study”. The purpose of the allocation procedures is to assess, as accurately as possible, the fundamental relationships between inputs and outputs, as well as their characteristics.

The following stepwise procedure, as outlined in the ISO 14040-44:2006 is applied to this study:

Step 1: Wherever possible, allocation should be avoided by:
a) Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes.
b) Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of (function, functional unit, and reference flow).

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurement such as mass or molar flows of co-products.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products (ISO, 1998, 2006).

LCI Modelling

There are two main LCI modelling frameworks, namely; consequential and attributional modelling. According to Curran *et al* (2005), consequential LCI takes into consideration how the flows may change when decisions change, while in attributional LCI, the flows in the environment are considered within a chosen time-based window. Wolf (2011) states that; "attributional LCA (ALCA) aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems, and consequential LCA (CLCA) aims to describe the environmental consequences of an analysed decision".

2.3.4.3 Life cycle impact assessment

The potential environmental impacts of the inputs and outputs in the LCI are evaluated in this stage. The impact assessment tries to link a product with its potential effect, rather that indicate the absolute risk or actual damage to the environment of human health (Koukouna, 2014). The environmental releases and potential human-ecological effects of the material, water and energy use. The key steps include:

Selecting and defining impact categories

Impact categories are considered in the first methodological step of LCA, but they may be reconsidered after data collection. The impact categories identified in LCIA include acidification, terrestrial toxicity, global warming, etc. and are given in the figure below.

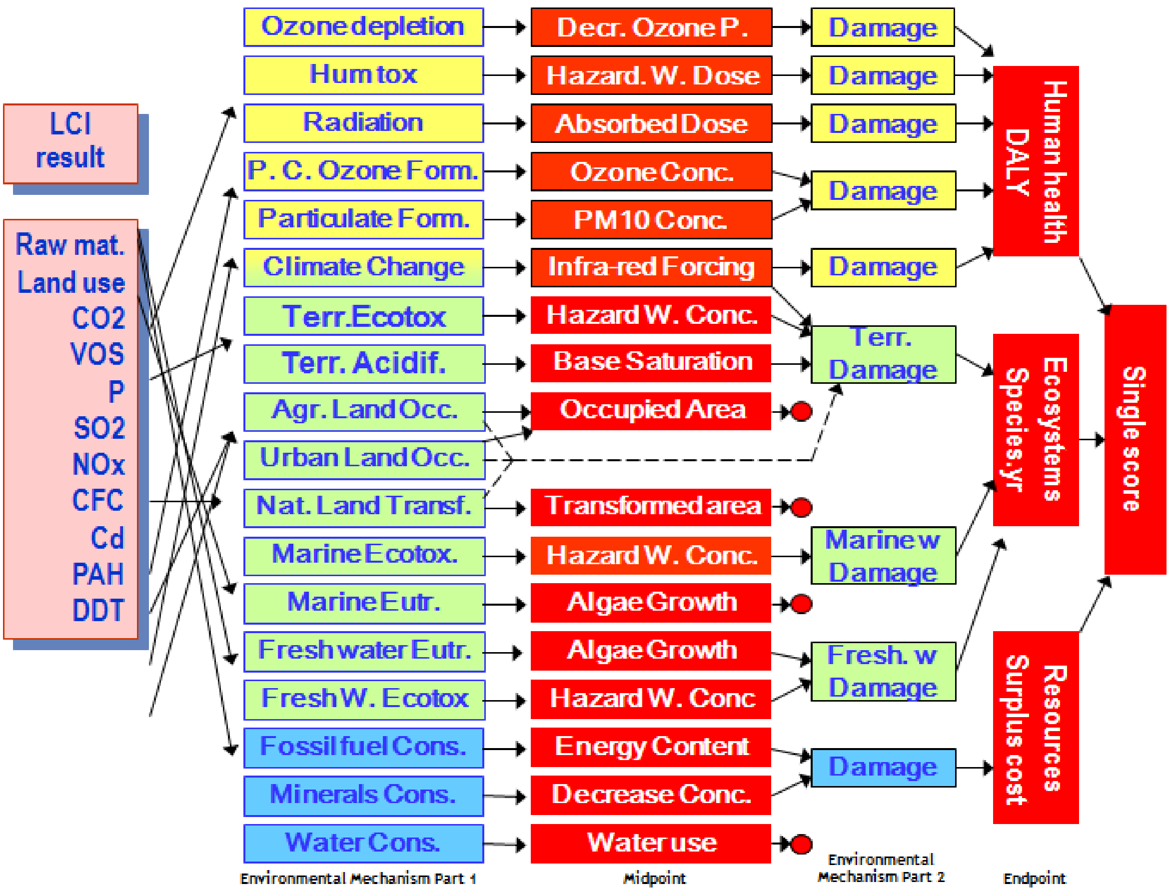

Figure 2.9 Example of impact categories considered in LCA studies

Source: ReCiPe (2008)

Classification

This stage attempts to assign LCI results to the impact categories. Classification is simple when an inventory item contributes to only one impact category, however a type of environmental release may contribute to two or more impact categories. ISO (1998) suggests two methods of dealing with this issue:

- When the environmental effects are independent of each other, all LCI results are assigned to all impact categories to which they contribute.
- When the effects are dependent on each other, partitioning is used to assign representative portions of the results to the impact categories.

Characterization

Conversion factors are used to translate different inputs from the inventory with each impact category. These characterization factors are scientifically derived and are used to combine and convert LCI results into respective human and ecological health impact indicators (ISO, 2006)

Normalization

This step is optional in ISO 14044:2006 to assist the interpretation stage. It is used to calculate the magnitude of the category indicator results. Normalization enables comparison of different environmental impacts by referring the impact scores to a common reference (Stranddorf *et al*, 2005).

Grouping

This step is a tool used to interpret the results into specific areas of concern by sorting and ranking the impact categories. Impact categories are therefore assigned to one or more groups (Koukouna, 2014).

Weighting

Weighting is also an optional step in ISO 14044:2006. Relative values or weights are assigned to the different impact categories based on apparent relevance or importance (SAIC, 2006).

Evaluation and reporting LCIA results

The evaluation of the accuracy of the LCIA results are verified after the calculation of the impacts of the selected categories. The accuracy of the LCIA results support the defined goal and scope (Stranddorf, 2005). It is also important to thoroughly describe all the methodological choices and assumptions during documentation of the LCIA results.

2.3.4.4 Life cycle interpretation

The last step of LCA is a systematic approach that is used to identify and evaluate LCI and LCIA results as well as communicate them effectively. This consists of three key steps, as reported by Koukouna (2014):

- Identifying significant issues;
- Evaluating the consistency, sensitivity and completeness of data; and
- Drawing conclusions and making recommendations.

3. LIFE CYCLE ASSESSMENT OF MAIZE COBS FOR ELECTRICITY GENERATION

Zych (2008) and Reese (2011) suggested that collecting maize cobs simultaneously with grain harvesting has numerous advantages over harvesting other residue parts alone. Coupling maize cob collection has benefits such as low nutrient removal from the soil, allows collection of sediment- or contaminant-free cobs, requires minor modification of harvesting equipment, avoidance of densification of cobs, cobs are easy to gasify due to low levels of nitrogen and silica.

Maize crop production begins with primary and secondary tillage, application of manure, planting and application of starter fertilizer, herbicide application before and after emergence, application of N fertilizer, grain harvesting and grain handling. Depending on the area in which maize is grown, irrigation and lime application may be required. These two activities depend on the soil available moisture (dependant on annual rainfall) and soil pH levels for the given area.

The amount of fuel or diesel used for each activity mentioned above will have an impact on the GHGs emitted. Maize grain requires additional drying using natural air and electricity (for circulation of air and operation of augers in grain handling) (Molenhuis, 2001; OMAFRA, 2009). Natural gas and electrical energy use can be calculated and expressed as GHG emissions. Due to slight modification on the combine harvester during grain and cob harvesting, additional diesel is consumed and will also need to be accounted for.

The average synthetic fertilizer N (SFN) application is reported to range between 91 and 146 $kgNha^{-1}$ (Jayasundara *et al*, 2014). Average P and K fertilizer application rates can be estimated by calculating the rate of P and K removal by harvesting grain, calculating the amounts of P and K input from manure application, and calculating the balance between P and K exported by grain. Fertilizer production mixing and transport will also be considered. These are expressed in terms of GHG emissions. Manure also contributes to N, P and K inputs. Since it is a waste from overstock, there are no production cost attributes associated with manure. However, diesel energy for loading, transport and application will have to be considered.

McGee *et al* (2010) reported that a survey done in 2008 in Ontario indicated that the average rate of herbicide use for maize was 1.89 kg per hectare. This figure has to be verified as surveys are done every five years and are site-specific. In order to determine the energy used to produce a certain herbicide, the types of herbicides for the given area need to be identified, for example, in some areas the most dominant types of herbicides are glyphosate (34 %), s- metolachlor (23 %), atrazine (29 %) and others (14 %) (Jayasundara *et al*, 2014). The energy consumption for herbicide is also affected by the energy used in formulation, packaging and delivery (Nagy, 1999). The information mentioned above will then aid the determination of the GHG emissions associated with production and supply of herbicide.

The energy consumed in the production of maize seeds depends on the type of seed used, i.e. hybrid seed maize production consumes more energy than commercial grain maize production (Graboski, 2002), the seeding rate of the kernels per hectare and the seed mass per kernel. These factors help to calculate the average seeding rate required for planting of maize and as a result the energy associated with production and use of maize seeds.

3.1 Goal and scope definition

In this step of the study, the products and/or services are clearly defined. The resources and time required to complete the study are defined. The methodological step also identifies the boundaries and environmental effects as well as establishes the context of the assessment.

3.1.1 Production routes

For the purpose of this research, different processes for production of electricity using biomass gasification will be studied. These are:

- Production of maize and extraction of maize cobs for generation of electricity using a fluidized bed gasifier,
- Production of maize and extraction of maize stover for generation of electricity using a fluidized bed gasifier,
- Production of wheat and extraction of wheat stalks for generation of electricity using a fluidized bed gasifier, and

- Extraction of coal for generation of electricity using the conventional method in South Africa.

3.1.2 Goal of the study

The goal of this LCA is to study the environmental impacts associated with the production of maize and extraction of maize cobs. It is to study the environmental impacts of producing electricity from maize cobs and to compare these impacts with those associated with electricity production from maize stover as well as from wheat stalks. The study also aims at comparing these impacts with those related to the conventional method of generating electricity in SA (coal power). It is important to note that the production of wheat and coal will not be studied in great detail; instead data will be obtained from literature, as these are mainly for the purpose of comparison.

The following questions are addressed in this LCA study:

- Which production route for electricity production, in this study, is the one with the lowest environmental impacts?
- What are the relative shares of contribution in different stages of production for the different feedstocks or processes?
- What are the environmental impacts associated with the feedstocks or energy crops investigated in this study?
- Which process is environmentally better for electricity production?

The answers to these questions should support decision making and policy for energy producers in the future. It should be noted that several questions are out of the scope of this study and cannot be answered by analysis made in this report. These questions include:

- Is it better to use the biomass for other applications, such as fuel like ethanol?
- Does it make sense to use the investigated energy crops to produce electricity or would it be better for them to be used to benefit agricultural land (e.g. as ground cover or fertilizer)?
- What are the social and economic impacts of the investigated processes or production routes?
- How sustainable is bioenergy?

Stakeholders:

The audience for this study (shown in Table 3.1) includes all people involved in the development of products used for the production of energy as well as energy/electricity producers. The results of this study can be used to improve the production of electricity from an environmental point of view.

Table 3.1 Potential audience for this LCA study

Stakeholder	**Possible Use of Results**
Resource suppliers (i.e. farmers, coal producers)	Assess their environmental competitiveness in the energy market
Energy producers	Improve the environmental performance of their processes Assess environmental competitiveness
Public users of LCI	Use the LCI for their own study
Government, policy makers and NGO's	Support political decisions
Researchers	Use information and knowledge for future projects

3.1.3 Scope of the study

This section defines the function, functional unit, reference flow and data requirements of the study.

3.1.3.1 Reference flow and functional unit

The function of interest for this study is the production of electricity. Energy crops are grown and cultivated, then feedstocks (maize cobs/stover and wheat stalks) are extracted and then used in the gasification process to generate electricity. The mining of coal and generation of coal power will be used for comparison. The functional unit is 1 kWh of electricity produced by the conversion process. The reference flow for the comparison of these processes is defined as the quantity (in mass) of feedstock required to generate 1 kWh of electricity.

3.1.3.2 System boundaries

The LCA within this report investigates the life cycle from land preparation for the production of maize to the conversion of maize cobs into electricity. Seed, pesticide and herbicide production, multiple cropping and capital goods are not included in the study. The study also excludes the distribution and actual use of electricity, maintenance, material storage and waste management.

The elementary flows which are recorded in the inventory will be based on the Ecoinvent database. These include energy inputs (fuel and electricity), use of ancillary materials (fertilizers, pesticides and herbicides), as well as emissions to air, water and land. Data representing noise, vibration, odour and waste heat will not be included, as data representing such elementary flows are rarely available and difficult to address in the LCIA. Direct impacts on workers and labour health are not addressed. Wastes and emissions related to waste management are not included in the LCI. The LCA study does not address economic and social aspects of the investigated life cycle.

The diagram below (Figure 3.1) shows the electricity generation process from maize residue, as well as the system boundary for this particular study.

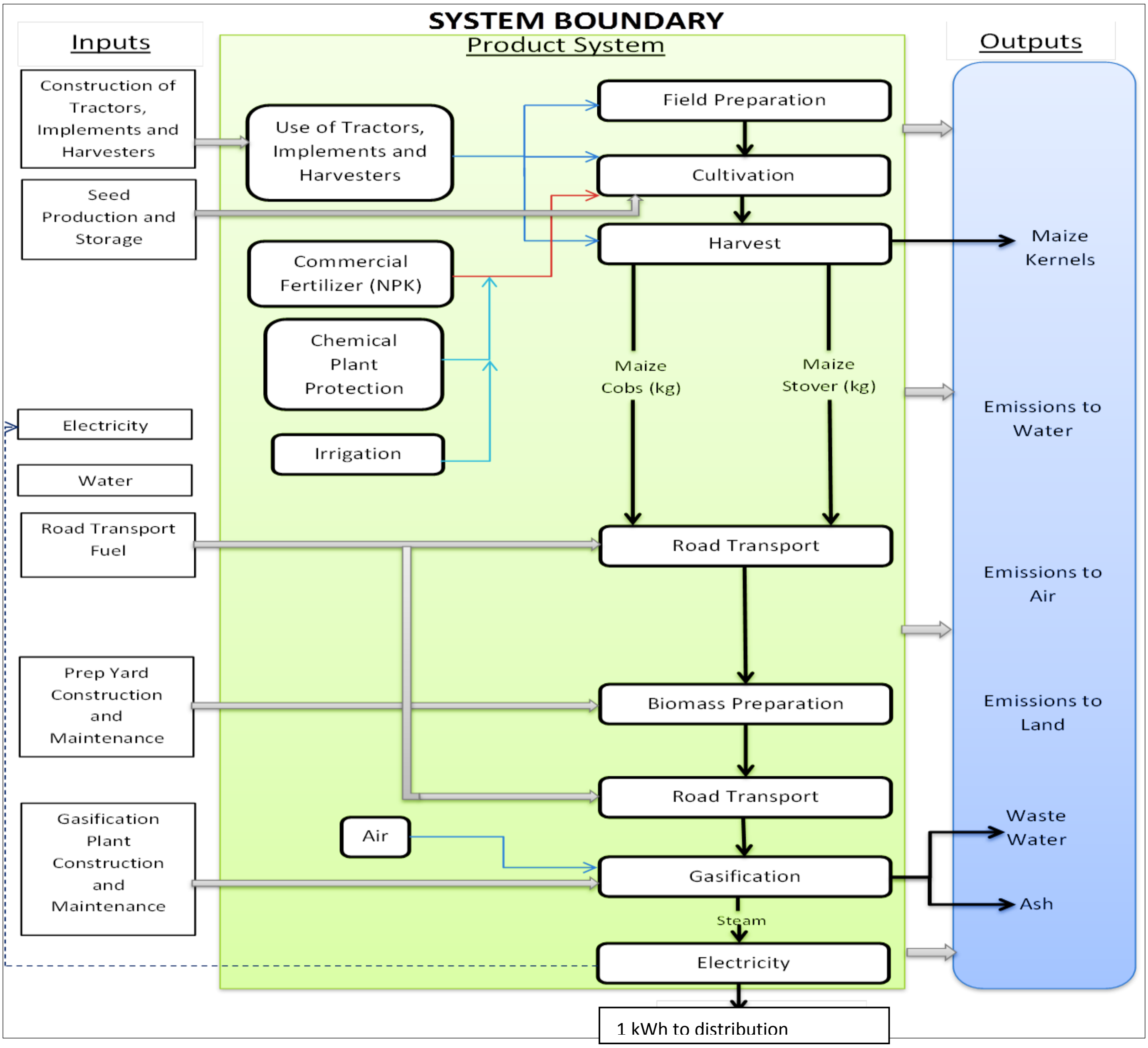

Figure 3.1 Process flow diagram for electricity generation from maize residue

3.1.3.3 Data quality requirements

This study follows the standards of the ISO on data quality in order to ensure that data is consistent and reliable, and to help ensure a precise evaluation of the results.

<u>Time-related coverage</u>

Time-related coverage describes the minimum amount of time over which data are collected as well as the age of data. Data are sourced from regularly updated sources such as the

International Journal of Life Cycle Assessment. The Ecoinvent library from SimaPro, which is a comprehensive database that was created and is regularly updated by six Swiss organizations, was also used. This ensures that the data applied to this study represent current practices and products. Data are based on data sets from the late 1900's to 2016. Greenhouse gas emissions are assessed for a period of 100 years.

Geographical coverage

Geographic coverage describes the geographical area from which data representing unit processes are allocated to fulfil the scope and goal of the study. Data representing the agricultural production of maize and the mining of coal are based on South African sources such as the FAO, ARC, DAFF and Eskom, and are a representative of South African systems. Data for material, energy, processes and transportation are mainly from international databases.

Technological coverage

Technological coverage related to the time period of the recorded data is current. Technological data for the materials and processes within the study are based on recent industry norms and standards, and developments. The gasification process is a fairly recent technology and as a result, data are mainly available for small-scale plants or feasibility studies. Therefore, data representing the environmental impacts of the process, that cannot be easily obtained, will be related to the future. The empiric knowledge of completed projects may be used to obtain data.

Elementary flows are modelled as far as possible with available background data from the Ecoinvent database as well as other published LCA data sources. Data representing materials such as fertilizers and services such as transport or electricity (and other elementary flows) are available in these data sources.

Data sources

The boundary of the system in this study (as shown in Figure 3.1) encompasses field preparation, cultivation, harvest, road transport, biomass preparation and gasification (electricity generation). The main data sources for these subsystems are provided in Table 3.2 below. These data sources include;

- industry and manufacturer reports and database,
- government reports, databases and documents,
- published documents (articles, journals, books, references),
- publicly available data and reports,
- related previous LCAs, and
- Government, processes, and equipment specifications and requirements.

To obtain the required data, several databases and software applications (SimaPro) are used. These include data based on quantitative research, observations and manufacturer information that are used to determine national averages.

Table 3.2 The stages of the life cycle of maize production and electricity generation, and the main data sources

Life Cycle	**Unit Processes**	**Main data sources**
1. Field Preparation	Machine time hours	DAFF (2013, 2016), AGRICO (2016),
	Tractor fuel consumption	
2. Cultivation	Machine time hours	DAFF (2013, 2016)
	Tractor fuel consumption	
	Irrigation	FAO, ARC, SABI
	Chemical plant protection and fertilizer application	BASF (2017)
3. Harvest	Machine time hours	DAFF (2013,2016)
	Combine and tractor fuel consumption	
	Maize harvest	Vermeer, John Deere

Life Cycle	Unit Processes	Main data sources
4. Transportation	Maize cob transportation to prep yard	DAFF (2016)
	Maize cob transportation to generation plant	
5. Gasification	Resource consumption	Wu *et al* (2014)
	Wastes generation	
	Electricity generation	Sebastian *et al* (2011)

<u>Uncertainties, assumptions and limitations</u>

The main assumptions for each subsystem are included in Table 3.3.

Table 3.3 Key assumptions

Life Cycle	Main Assumptions
1. Field Preparation 2. Cultivation 3. Harvest	Cultivation of irrigated grain maize Maize harvested at 21 % moisture content (FAO, 1992) 1 ha ≡ 8 t of grain 6.5 t biomass required to generate 1 kWh electricity Wu *et al* (2014) Cultivation area of 22 ha (based on cob yield) Cultivation with a cycle of 1 year
4. Transportation	Maize cob transport over an average distance of 10 km
5. Biomass preparation 6. Gasification	Biomass preparation involves sizing and sorting, which is done manually Fluidised bed gasifier is used (based on Table 3.2) 1 kWh electricity generated

3.2 Life cycle inventory

In this stage of the life cycle assessment, all inputs and outputs of the process are quantified. The inputs include raw material and energy, while outputs include any material emissions to the environment; such as water, air, and solid waste. SimaPro is used in this study to structure and calculate the inventory data.

3.2.1 Data collection

As different production systems are compared in this study, quantitative and qualitative data will be used. The data to be included in the inventory are collected for each unit process that is included within the system boundary.

3.2.1.1 Allocation

The production of maize yields three co-products under the system in this study; which are grain, cobs and stover. There is therefore a need to determine an appropriate method to allocate the impacts of the system between the products. The Handbook on LCA recommends economic allocation as the baseline method for most allocation situations in a detailed LCA. Economic allocation assigns impacts proportional to the value of the co-products. To calculate the allocation factors for the product and co-products of concentration in this study (cobs, grain and stover) the following equation is used:

$$Allocation\ factor = \frac{Market\ value\ of\ product}{Market\ value\ of\ crop} \tag{3.1}$$

The following data were used:

The average yield of maize grain in South Africa for the 2016/2017 season is 4.0 $t.ha^{-1}$, as reported in Chapter 2, section 2.1 of this report. Irrigated maize results in double the yield of dryland maize (du Plessis, 2003). The yield used in this study is, therefore, 8.0 $t.ha^{-1}$, in order for the results to account for the most extreme case in terms of water use. The average market price of maize used in the calculation is for the latest reported data for March 2017, which is R3 834.00 per tonne (see Section 2.3.2). The average cost of maize residue at farm gate in the Mpumalanga Province is \$24.00 per tonne (Batidzirai *et al*, 2016). The Rand to Dollar exchange rate of R13.38 as at 05 May 2017 was used to convert this value to R321.12 per tonne. Using this data, cob and stover yields can be determined, based on equations derived from Maung and Gustafson (2011).

$$R_{cob} = Grain\ yield\ \times\ CGR\ \times (Removal\ \%)\ \times\ (1 - Moisture\ \%) \tag{3.2}$$

R_{cob} is the quantity of collected maize cobs in tonnes per hectare. CGR cob-to-grain ratio, calculated as 1:5.6, based on Wiselogel *et al* (1996). Removal % is the percentage of maize cobs which can be removed sustainably from the field each year. CVEC (2009) and Roberts (2009) stated that maize cobs have limited nutrient value to the soil and that their removal has negligible impact of soil properties. It was, therefore, assumed that 100 % of cobs are removed. Moisture % is the moisture content of the maize cobs at harvest. The moisture content of maize cobs at harvest is assumed to be 21 % (a midpoint of the values reported in Table 3.3 of this report).

From Equation 3.2 the quantity of collected maize cobs is determined as follows;

$$\therefore R_{cob} = 8.0\ t.ha^{-1} \times \frac{1}{5.6} \times 1 \times \frac{100-21}{100}$$
$$= 1.13\ t.ha^{-1}$$

Similarly;

$$R_{stover} = Grain\ yield \times SGR \times (Removal\ \%) \times (1 - Moisture\ \%) \tag{3.3}$$

Rstover is the quantity of removable stover in dry tonnes per hectare. SGR is defined as the stover-to-grain ratio, which is assumed to be 1:1 based on Perlack and Turhollow (2003), Kim and Dale (2004), Nelson *et al* (2004), and Hiliodhari and Baruah (2011). Removal % refers to the percentage of stover that can be removed sustainably as feedstock for biomass energy production. Taking into consideration, the information given in Section 3.3.1; it is assumed that 40 % of stover can be removed from the field. Similar to cobs, the moisture content of the stover is assumed to be 21 %. From Equation 3.3, the percentage of stover that can be removed is;

$$\therefore R_{stover} = 8.0\ t.ha^{-1} \times 1 \times \frac{40}{100} \times \frac{100-21}{100}$$
$$= 2.53\ t.ha^{-1}$$

The allocation factor for maize cobs can therefore be determined as follows;

$$Allocation\ factor\ for\ cobs = \frac{R_{cobs} \times price\ of\ residue}{Grain\ yield \times price\ of\ grain + [(R_{stover} + R_{cob}) \times price\ of\ residue]} \quad (3.4)$$

The calculated values are given in the Table 3.4 below.

Table 3.4 Allocation factors for maize products

Product or co-product	Allocation factor
Cobs	0.011
Stover	0.025
Grain/Kernels	0.963

3.2.1.2 LCI modelling

Frischknecht and Stucki (2010) suggest that ALCA is more appropriate for studies with results that provide information about environmental impacts of fuel supply chains, operation of power plants, the generation and distribution of electricity etc., that are due to the use of 1 kWh of electricity, for example. The study also indicates that the use of CLCA is more appropriate for studies that are aimed at linking micro-economic actions with macro-economic outcomes.

Based on recommendation made by Frischknecht and Stucki (2010) attributional modelling is used in this study as it quantifies life cycle impacts by accounting for environmental physical flows to and from the production of energy feedstock, transportation, electricity generation. Also, the values used are averages based on normal, current industry practices. Since this LCA study does not include any indirect effects that are not directly related to the production of maize and extraction of maize cobs for electricity production; ALCA is a more appropriate model than CLCA.

3.2.1.3 Data inventory of unit processes

The unit processes under study are ‘field preparation’, ‘cultivation’, ‘harvest’, ‘transport’, ‘biomass preparation’, and ‘gasification’. The allocation factors calculated above are applied to all inputs and outputs associated with multi-functional processes (delivering more than one product or service – co-products). The tables below represent the main inputs and outputs of each unit-process for a comprehensive overview of the system under study.

Field preparation

All inputs and outputs are based on 1 kWh of electricity produced through gasification. The lifetime of a maize plant is about six months (Moeletsi and Walker, 2012), the same period is used as the lifetime of 'field preparation'. The emissions of this process are due to machinery, raw material and energy use. Table 3.5 shows all the material and energy the inputs required for field preparation.

Field preparation includes primary and secondary tillage. Primary tillage loosens the soil in order to counter compaction and improve the structure of the soil. Secondary tillage is for weed control and seedbed preparation. A mouldboard plough attached to a tractor is used for primary tillage, while secondary tillage involves the use of harrows. Other actions employed during field preparation may include debushing, removal of stones and rocks, ripping and levelling of the soil, as well as application of organic matter and starter fertilizer (lime).

Table 3.5 Material inputs and outputs in field preparation

INPUTS		**OUTPUTS**	
Tractor	See below	Cleared land, to cultivation	22 ha
Plough	See below		
Ripper	See below		
Leveller	See below		
Fuel consumption by machinery	3 753 kWh		
Organic matter	14.96 t		
Lime	11 000 kg		
Unmanaged land	22 ha		

Field preparation only occurs once during the lifetime of maize production. Machinery use is calculated based on the lifetime of the machinery compared to its actual operation time, which is allocated to the lifetime of the crop. Table 3.6 shows operation time for all the machinery employed in field preparation. It is important to note that the implements listed in the table are either mounted to or trailed by a tractor.

Table 3.6 Activity duration times for implements and tractor employed in field preparation

ACTIVITY	IMPLEMENT	SPECIFICATIONS			DURATION	TOTAL OPERATION TIME
	Description	Working width (A)	Working Speed (B)	Effectiveness (C)	$\frac{10000}{A + B \times 1000 \times \frac{C}{100}}$	
		m	$km.hr^{-1}$	%	$hr.ha^{-1}$	hr
Plough	3-furrow mounted mouldboard plough	1.22	3.3	83	2.99	66
Ripper	3-tine mounted V ripper	1.20	8.0	85	1.23	27
Leveller	25M/30 trailed leveller	3.00	4.0	85	0.98	22
Secondary Tillage	Tandem disc harrow	3.00	9.2	83	0.44	10
Lime	3-tine trailed lime spreader	3.00	8.0	60	0.69	15
Tractor	60 kW, 4WD tractor					139

The tractor specifications based on DAFF (2016) guidelines are as follows;

Table 3.7 Tractor specifications

Tractor size	Power demand	Litres used per kWh	Fuel consumption (l/hr)
60 kW, 4 WD	Medium	0.35	9.45

The total amount of fuel consumed for preparation of 22 ha of land is calculated as follows;

$$Fuel\ consumption = 9.45\frac{l}{hr} \div 0.35\frac{l}{kWh} \times 139\ hr$$
$$= 3\ 753\ kWh$$

It is assumed that the organic matter applied for the purpose of soil mulching and to minimize erosion is the amount of stover that remains on the ground after grain and cob harvest. When stover is removed for use of electricity generation, the same amount of alternative organic matter is assumed.

Agricultural lime consists of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), as reported by Ogle *et al* (2014). Tongwane *et al* (2016) cited that based on Otter *et al* (2010); applied agricultural lime consists of 37 % limestone and 63 % dolomite. For maize production, two tonnes of lime per hectare is applied every four years (Tongwane *et al*, 2016). It is therefore assumed that lime inputs are distributed evenly on an annual basis (i.e. 500 kg.ha^{-1} of lime is applied per season).

<u>Cultivation</u>

Emissions from this process are attributed to energy, raw material and machinery inputs. Cultivation of maize involves application of fertilizer, chemical plant protection, irrigation and planting. du Plessis (2003) recommends application of not more than 50 kg.ha^{-1} of each nitrogen, phosphate and potassium fertilizer for 1.5 m rows of maize. Limestone ammonium nitrate (LAN) is applied as a source of nitrogen, single superphosphate (SSP) as P_2O_5 is applied as source of phosphorus, while muriate of potash is used as a source of potassium (FAO, 2005).

Table 3.8 Material inputs and outputs in cultivation

INPUTS		**OUTPUTS**
Cleared land, from field preparation	22 ha	Cultivated plants
Maize grain	176 t	
Irrigation water	166 433 m^3	
Electricity for irrigation	32 757 kWh	
NPK fertilizer - N source - P source - K source	[150 kg.ha^{-1}] 1 100 kg 1 100 kg 1 100 kg	
Chemical plant protection	See below	

Tractor	See below	
Fertilizer spreader	See below	
Chemical sprayer	See below	
Planter	See below	
Fuel consumption by machinery	284 kWh	

Fertilizer and plant protection chemicals are dissolved in water and applied through a fertilizer spreader and chemical sprayer, respectively. The operation time of these implements are given in Table 3.9. These implements are mounted on a 60 kW, 4 WD tractor, as in field preparation.

Table 3.9 Activity duration times of implements and tractor employed in cultivation

ACTIVITY	**IMPLEMENT**	**SPECIFICATIONS**			**DURATION**	**TOTAL OPERATION TIME**
	Description	**Working width (A)**	**Working Speed (B)**	**Effectiveness (C)**	$\frac{10000}{A + B \times 1000 \times \frac{C}{100}}$	
		m	**km.hr^{-1}**	**%**	**hr.ha^{-1}**	**hr**
Fertilize	4 000 litre mounted double-disc spreader	3.2	3.2	85	1.15	25
Spray	12 m, 1 000 litre mounted boom sprayer	12	6.0	85	0.16	4
Plant	3 row, 1.5 m mounted air maize planter	1.5	3.0	85	2.61	57
Tractor	60 kW, 4WD tractor					86

The machinery works for a total of 86 hours according to Table 3.9 above. The total fuel consumption can therefore be calculated as follows:

$$Fuel\ consumption = 9.45\frac{l}{hr} \div 0.35\frac{l}{kWh} \times 86\ hr$$
$$= 284\ kWh$$

Guidelines from BASF (2017) were used to obtain data for herbicide, fungicide and pesticide application. These are given in Table 3.10.

Table 3.10 Chemical treatment application for maize cultivation

Chemical treatment	**Active ingredient(s)**	**Number of applications**	**Application rate (ℓ.ha^{-1})**	**Total applied* (kg)**
Fungicide 1	Triazole 62.5 g/ℓ	2	1.6	4.4
Fungicide 2	Benzimidazole 125 g/ℓ	2	50.5	277.8
Herbicide 1	Dimethenamid – P (Chloroacetamide) 720 g/ℓ	1	1.25	19.8
Herbicide 2	Atrazine 420 g/ℓ	4	3.0	110.9
Pesticide	Alpha-cypermethrin (Pyrethroid) 100 g/ℓ	9	0.125	2.475

*The total chemical treatment applied is calculated as follows:

$$Total\ applied = application\ rate\ \times mass\ content\ \times no.of\ applications\ \times area^{**}$$

**Area = 22 ha (as indicated above)

<u>Irrigation</u>

In order to determine the total amount of water and energy used to irrigate 22 ha of maize during the production season; a simplified irrigation system design was done. The calculations are to aid the estimation of the required data and do not represent a full design, as a number of factors like topography, system losses, lateral and mainline pipe designs, filtration system, etc. are not included.

Preliminary design

Water loss in plants occurs due to evaporation and transpiration (or evapotranspiration). The amount of water required to meet the water loss is known as ET_c. It is the amount of water required by the crop for optimum growth. The crop water need depends on the crop type, climate and growth stages of the crop. The first step in determining crop water requirements is the determining the cropping pattern.

In South Africa, maize can be either planted in December and harvested in April or planted in October and harvested in February (ARC, 1996). For the purpose of this study, the December – April growing season is assumed, as it represents high evapotranspiration months in SA.

The ARC Irrigation Design Manual (1996) is used to obtain monthly crop factor (K_c) and reference evapotranspiration (ET_o) values.

The crop factor values are representative of all climatic regions, while ET_o values represent the area with the highest evapotranspiration and relatively low mean annual precipitation (MAP). The nearest rainfall station (from WeatherSA) is used to obtain monthly rainfall data for this area. This data (recorded in Table 3.11) is used to determine irrigation requirements.

Table 3.11 Crop water and irrigation requirements for maize

Planting date: December 2016												
Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
ET_o (mm/day)	9.70	8.70	6.80	5.00	3.60	2.90	3.10	4.20	5.50	7.10	8.50	9.40
K_c per month	0.75	1.14	1.14	0.93								0.39
ET_c (mm/d)	7.28	9.92	7.75	4.65	0	0	0	0	0	0	0	3.67
No. of days	31	28	31	30	31	30	31	31	30	31	30	31
ET_c (mm/m)	225.53	277.70	240.31	139.50								113.65
P (mm/m)	8.63	0.00	4.83	17.52								13.97
P_e (mm/m)	-4.82	-10.00	-7.10	0.51								-1.62
IN (mm/m)	230.35	287.70	247.41	138.99								115.26
IN (mm/day)	7.43	10.28	7.98	4.63								3.72
Total Nett Irrigation Requirement (NIR) (mm/cycle)												**1019.72**
Total Gross Irrigation Requirement (GIR) (mm/cycle) - Drip Efficiency = 95%												**1073.34**
Total Gross Irrigation Requirement (GIR) (m^3/cycle/ha)												10733.86

Note:

ET_c (mm/day) = K_c (per month) × ET_o (mm/day)

ET_c (mm/month) = 30 × ET_c (mm/day)

$P_e = 0.6 P - 10$ if $P < 75$ mm/month

$P_e = 0.8 P - 25$ if $P > 75$ mm/month

IN (mm/month) = ET_c (mm/month) - P_e (mm/month)

Maize can be grown successfully in variety of soils ranging from loamy sand to clay loam (du Plessis, 2003). It is assumed that water used for irrigation is pumped from a river. Pressure compensating dripper lines were assumed. The Netafim catalogue was used to select the drippers.

Table 3.12 Irrigation system design parameters

CROP DATA	
Crop Type	Maize
Crop Factor	1.14 (peak crop water requirement occurs in February)
Salt sensitivity (EC_e)	170 mS/m (ARC Irrigation Design Manual)
Natural Root Depth	600 mm (ARC Irrigation Design Manual)
Allowable Water Depletion	55 % (ARC Irrigation Design Manual)
CLIMATE	
Effective Rainfall	0 (worst case scenario)
Reference Evapotranspiration	8.70 mm/day (peak crop water requirement occurs in February)
SOIL	
Type	Sandy loam (assumed)
Clay content	10 – 20 % (from soil texture triangle)
Water Holding Capacity	100 mm/m
Infiltration rate	20 – 30 mm/hr (for sandy loam) (source: FAO, 2001)
WATER	
Electrical conductivity (EC_w)	155 mS/m (Acceptable for irrigation) (Source: DWA, 1996)
DRIP IRRIGATION SYSTEM	
System Efficiency	0.95 (SABI Norms)
Emitters	Pressure compensating drippers (assumed)
Lateral Spacing (S_p)	1.5 m (equal to row spacing of maize plants)
Emitter Spacing (S_e)	0.3 m (Netafim catalogue)
Flow Rate	1.0 l/hr @ 1 bar (Netafim catalogue)
Working Hours per Day	10 hours (7h00 to 17h00 - assumed)

The detailed calculations of the following parameters of crop water and irrigation needs are shown in Appendix 1.

Crop water requirement, ET_C

It is the loss of water through transpiration of the growing plant plus evaporation from the soil.

$$ET_c = K_c \times ET_o = 9.92\ mm/day$$

Leaching requirement ratio, LR

The leaching requirement is the minimum amount of irrigation water that is needed to pass through the root zone to control the salts within the tolerances of that particular cultivar, taking into consideration the quality of the water used.

$$LR = \frac{EC_w}{5EC_e - EC_w} = 0.223$$

Nett irrigation requirement, NIR

It is the depth of irrigation water necessary to meet crop water requirement.

$$NIR = \frac{ET_c}{1 - LR} = 12.77\ mm/day$$

Readily available water, RAW

This is the depth of soil water available within the effective root depth of the crop.

$$Available\ water, AW = WHC \times ERD = 60\ mm$$

$$RAW = AW \times \frac{\propto}{100} = 33\ mm$$

Percentage wetted area, P_W

It is the average horizontal area wetted crop root zone depth in relation to the total cropped area. According to Savva and Frenken (2002), the desirable P_w for widely spaced crops has a minimum of 33 % and maximum of 67 %. According to Keller and Bliesner (1990), P_w often approaches 100 % for closely spaced crops with rows and drip laterals spaced less than 1.8 m apart and according to Savva and Frenken (2002), the area wetted by one emitter for sandy loam is 1 m^2.

$$P_w = \frac{100 \times N_d \times S_e \times D}{S_p \times S_e} = 73\ \%$$

Cycle length, t_c

The actual time lapse between beginning of two successive applications for a specific irrigation set.

$$t_c = \frac{RAW \times P_w}{NIR_d} = 2\ days$$

Gross irrigation requirement per cycle, GIR_c

This figure is determined by incorporating system efficiency.

$$GIR_c = \frac{NIR}{\eta} \times t_c = 26.88\ mm$$

Stand time, t_s

It is the period for which a system has to irrigate to apply the design application. To calculate the application rate (also known as precipitation rate), divide the emitter flow rate (l/h) by area covered per emitter. The application rate will be based on the wetted strip.

$$AR = \frac{q_e}{D \times S_e} = 3.03 \frac{l}{hr.m^2}$$

$$t_s = \frac{GIR_c}{AR} = 8.87\ hr$$

Theoretical size of irrigation group

Operating hours per cycle (t) = t_s x t_c x shift number = 8.87 x 2 x 2 = 35.5 hrs, the system capacity is:

$$Q = \frac{GIR_C \times A_T \times 10}{t} = 166.6\ m^3/hr$$

It is assumed that the system applies 166.6 $m^3.hr^{-1}$ for about 9 hours, every 2 days, when the drippers are operating together. The system works for a total of 111 days during the season.

The total amount of water required to irrigate the 22 hectares of maize for the entire period can then be determined as follows;

$$V_{total} = Q \times t_s \times no. of\ irrigation\ days = 166\,433.4\ m^3$$

Mainline

The mainline is a pipe with which water is pumped from the river to the inlet positions of the irrigation blocks. A length of 1000 m and diameter of 200 mm were assumed for the mainline. SABI design suggest that for rising main lines with a diameter of 200 mm or smaller, a maximum of 1,5 m friction for each 100 m pipe length (1,5%) is allowed. A maximum of 2 m of pressure is lost along the mainline (SABI norms). The discharge pressure and elevation were both assumed to be 10 m. The total dynamic head can be calculated as follows:

Total dynamic head = static head (elevation) + discharge pressure + pressure loss + friction loss

= 10 m + 10 m + 2 m + 15 m = 37 m

The South African Irrigation Institute (SABI) norms suggest an addition of 5 % safety factor to determine the total system head, which is 39 m.

Pump system

Centrifugal pumps are the most common type used for irrigation. It is assumed that water is pumped from a nearby river, through a submersible pump. The calculated system capacity and total head were used to select a pump from the pump selection curve in Appendix 2. The following specifications were then determined from the performance curves in Appendix 3;

Table 3.13 Pump design parameters

Pump pressure head	42.5 m
Pump delivery rate	170 m^3/hr
Type and model	NK 80-200
Diameter of impeller	195 mm
Pump speed	2900 rpm
Duty point efficiency	80.7 %
Power required at pump shaft	24.5 kW
$NPSH_{required}$	3 m

The available net positive suction head (parameters given in Table 3.14) must be larger than the required net positive suction head to ensure optimum function of the pump.

Table 3.14 Nett positive suction head design parameters

Atmospheric pressure (h_d): Figure 16.23 RSA irrigation Manual	10 m
Suction losses (h_f) (assumed)	0.5 m
Vapour pressure of water (h_{vp}): Figure 16.23 RSA irrigation Manual	0.2 m
Static suction head (h_s)	4 m

$$NPSH_{available} = h_d - h_f - h_{vp} - h_s$$
$$= 10 - 0.5 - 0.2 - 4$$
$$= 5.3\ m$$
$$\therefore NPSH\ is\ in\ order\ because\ NPSH_{available} > NPSH_{required}$$

Drive System

An electric motor will be used to drive the pump. A cast iron motor with the following specifications was selected from BMG (2009);

Table 3.15 Drive system design parameters

Power source	Electrical
Type and model	Cast iron induction motor (Y3-200L1-2)
Shaft speed	2950 rpm
Rated power output	30 kW
Efficiency	91.5 %
Power factor	0.9
Full load current	52.6 A
Voltage	400 V

KVA Demand

$$P_i = \frac{P_{out}}{\eta} \times 100$$
$$= \frac{30}{91.5} \times 100$$
$$= 32.79\ kW$$

$$KVA = \frac{P_i}{power\ factor}$$

$$= \frac{32.79}{0.9}$$

$$= 36.43\ kVA$$

It is therefore, assumed that a 50 kVA transformer is used. Low voltage electrical power is required to operate the irrigation system. The amount of energy required to operate the system for the entire season is;

$$Energy = P_i \times t_s \times no.of\ irrigation\ days$$

$$= 32.79 \times 9 \times 111$$

$$= 32\ 757.21\ kWh$$

Harvest

Harvest of maize grain is done by means of a combine harvester driven through the field. Crops are gathered in by the header at the front of the combine and pushed down towards a cutter bar by a rotating wheel called a reel. The cutter bar contains teeth (or mowing fingers) which open and close to cut the crops at ground level. The cut crops then travel to the processing mechanism inside the main part of the combine where grains are beaten and shaken off their stalks by a threshing drum. A tank below collects the grain which is offloaded into a trailer pulled behind the tractor that drives alongside the combine. When the tank is full, an elevator carries the grain up from the tank and offloads into the trailer through a side pipe.

In conventional combines, the residue (stover and cobs) tumbles from the back and is spread over the field. Recent technology allows grain and cobs to be harvested simultaneously and separately, in a single pass. A special trailer (called a cob caddy/harvester) is towed behind the combine to collect the cobs and redistribute leaves and stalks back onto the field. Some of the stover can then be baled for use as animal feed and bedding or as feedstock for biomass energy.

In the Ecoinvent database one bale weighs 700 kg, the number of bales that can be harvested from 22 hectares of cultivated maize is calculated by dividing the yield of stover by the mass of one bale.

Table 3.16 Material and resource inputs and outputs for harvest stage

INPUTS		**OUTPUTS**	
Cultivated maize plants, from cultivation		Maize cobs	24.83 t
Tractor and trailer transport	182.6 t.km		
Combine harvester	22 ha	Maize stover	55.62 t
Cob harvester	461.82 kWh		
Baler	22 bales	Maize grain	176 t

Since the assumed row spacing is 1.5 m, it is also assumed that a 3-row, 1.5 m snapper self-propelled combine is used for harvesting the grain. It is also assumed that a self-contained cob harvester is used for cob collection. The combine can harvest 8 tonnes of grain in one pass. A 4-wheel trailer of 8 tonne capacity, with dropside, pulled by a 98 kW, 4 WD tractor is used to transport the harvested grain to a silo located on the farm, a distance of 1 km. A similar tractor and trailer system transports harvested cobs from the cob harvester and offloads then onto a tractor at the farm gate, also assumed to be located 1 km away from the field.

The cob harvester has the following specifications, according to the Vermeer catalogue:

Table 3.17 Cob harvester specifications and calculated fuel consumption

TANK CAPACITY (kg)	**POWER (kW)**	**DURATION ($hr.ha^{-1}$)**	**CALCULATED TOTAL OPERATION TIME (hr)**	**CALCULATED FUEL CONSUMPTION (kWh)**
3 600	86	0.244	5.37	461.82

Transport

The Kendal Power Station, located in Mpumalanga, is the largest indirect dry-cooling power station in the world and is located less than 10 km from its main coal source (Eskom, 1994). To make this biomass power data comparable to that of coal power, the same distance between the farm gate and the power plant is assumed. The cobs are offloaded onto a 7-tonne truck at the farm gate, which transports them to the preparation yard, located 2 km from the farm. From the preparation yard, the feedstock is transported to the generation plant, located 8 km from the prep yard, using the same truck.

Gasification

The maize cobs from the preparation yard are used in the gasification process, without moisture removal. Table 3.3 shows that 6.5 tonnes of maize cobs are required to generate 1 kWh of electricity through gasification, the rest of the harvested maize cobs are assumed to be losses in the preparation yard. The inputs and outputs for this stage are given in Table 3.18.

Table 3.18 Material and resource inputs and outputs for gasification stage

INPUTS		**OUTPUTS**	
Maize cobs, from prep yard	6.5 t	Electricity	1 kWh
Oxygen, in air	5207 kg		
Heat energy	65 GJ	H_2O	

The information on gasification is based on Wu *et al* (2014). The first step of gasification is drying. The moisture content of the maize cobs is assumed to be removed completely during this step. This occurs at 101 °C and steam is released. This is shown in the equation below;

$$Cobs\ (wet) \rightarrow Cobs\ (dry) + \ H_2O\ (steam)$$

The cobs are then converted into char, ash, tar and molecular gases, during the pyrolysis process, as shown below;

$$Cobs\ (dry) \rightarrow char + ash + \ \alpha_1 CO + \ \alpha_2 H_2 + \ \alpha_3 CO_2 + \ \alpha_4 H_2O + \ \alpha_5 CH_4 + \ \alpha_6 tar$$

The char is then oxidized in the combustion process. The process yields CO_2 as shown below;

$$C + O_2 \rightarrow CO_2$$

To determine the stoichiometric air quantity used in the combustion process, the molecular weights are added in the chemical equation. By mass, air contains 23.2 % oxygen and 76.8 % incombustible gases. The amount of oxygen required to combust 1 kg of carbon is 2.67 kg (i.e. 32 ÷ 12). According to Brownsort (2009) and Woods and Hall (1994), pyrolysis typically yields 25 - 35 % of char, 30 % (the mean value) is assumed in this report. The amount of oxygen required for combustion is therefore;

$$O_2\ required = 6.5\ t \times \frac{30}{100} \times \frac{2.67\ kg}{1\ kg}$$
$$= 5\ 206.5\ kg$$

During the last step, the residual tar is decomposed further into molecular gases or syngas.

$$tar \rightarrow \beta_1 CO + \beta_2 CO_2 + \beta_3 H_2 + \beta_4 CH_4$$

The synthetic gas is used to wind turbines and produce electricity. Sebastian *et al* (2012) suggests that 1 kg of biomass consumes about 10 MJ of heat energy. It can therefore be deduced that the maize cobs consume 65 GJ of heat energy, which is assumed to be by natural gas.

3.2.1.4 Inventory data

The data calculated in this chapter, inform the selection of material, energy and resource inputs and allows the calculation of environmental emissions on SimaPro 8.3.0.0. The data are summarised in Table 3.19, with brief explanations of how these were selected from the database. The Ecoinvent version 3.4 database was used.

Table 3.19 Data inventory on SimaPro and justification

SimaPro 8.3.0.0			
Project	Maize cobs - South Africa		
PROCESS	**QUANTITY**	**UNIT**	**NOTES**
Products			Allocation %
Maize cobs	24.53	ton	1.14
Maize grain	176.0	ton	96.31
Maize stover	55.62	ton	2.55
Avoided products			
-	-	-	-
Resources			
Transformation, to annual crop, irrigated	22	ha	Transformation of grassland into arable land for annual crop production.
Oxygen, in air	5 206.5	kg	Required for combustion of char.
Materials/fuels			
Tractor, 4-wheel, agricultural {RoW}| production | Alloc Def, U	3 100	kg	Based on 60 kW, 4 WD John Deer tractor, used for primary tillage.
Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Alloc Def, U	1 728	kWh	Diesel burned by 60kW tractor used for ripping, levelling and spreading of lime.
Lime fertilizer, at plant/RER Economic	1 1000	kg	No primary data could be found on limestone fertilizer production on the selected database. Material from another database was selected.

Tillage, ploughing {RoW}| processing | Alloc Def, U	22	ha	The inventory takes into account the diesel fuel consumption and the amount of agricultural machinery and of the shed, which has to be attributed to the ploughing.
Tillage, harrowing, by rotary harrow {RoW}| processing | Alloc Def, U	22	ha	Included activities end: The inventory takes into account the diesel fuel consumption and the amount of agricultural machinery and of the shed, which has to be attributed to the harrowing.
Maize stover	33.37	ton	Amount of stover left on the ground for cover and mulching.
Maize seed, for sowing {GLO}| market for | Alloc Def, U	550	kg	This activity start with the transport to the seed processing centre.
Irrigation {RoW}| processing | Alloc Def, U	166 433	m3	The inventory includes the processes of water pumping (from a depth of 48m), machine infrastructure and a shed for machine sheltering. The water used is also included (as ground water).
Nitrogen fertiliser, as N {GLO}| market for | Alloc Def, U	539	kg	No primary data on LAN was found on the database. An alternative nitrogen fertilizer was used.
Phosphate fertiliser, as P_2O_5 {GLO}| market for | Alloc Def, U	1 078	kg	SSP fertilizer has similar chemical properties to the generic phosphate fertilizer.
Potassium chloride, as K_2O {GLO}| market for | Alloc Def, U	539	kg	No primary data on MOP fertilizer, the closest alterative available is potassium chloride fertilizer.
Atrazine {GLO}| market for | Alloc Def, U	110.88	kg	
Dimethenamide {GLO}| market for | Alloc Def, U	19.8	kg	
Benzo[thia]diazole-compound {GLO}| market for | Alloc Def, U	277.8	kg	Equivalent to Benzimidazole

Pyrethroid-compound {GLO}| market for | Alloc Def, U	2.475	kg	
Fertilising, by broadcaster {RoW}| processing | Alloc Def, U	22	ha	Has 500 litre carrying capacity and is adequate for the amount of fertilizer required. The inventory takes into account the diesel fuel consumption and the amount of agricultural machinery and of the shed, which has to be attributed to the fertilising.
Application of plant protection product, by field sprayer {RoW}| processing | Alloc Def, U	22	ha	Has 800 litre carrying capacity, 15 m working width and is able to spray the required amount in one pass. The inventory takes into account the diesel fuel consumption and the amount of agricultural machinery and of the shed, which has to be attributed to the application of plant protection.
Planting {RoW}| processing | Alloc Def, U	22	ha	
Combine harvesting {GLO}| market for | Alloc Def, U	22	ha	
Transport, tractor and trailer, agricultural {GLO}| market for | Alloc Def, U	182.6	tkm	Transport grain from combine to silo, 1km from field. transport cobs from cob harvester to lorry at farm gate, 1 km from field.
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Alloc Def, U	461.82	kWh	To account for the cob harvester. Fuel used by cob harvester, operating 5.4 hrs in total
Baling {RoW}| processing | Alloc Def, U	22	p	Baling of 22 bales of maize stover, each weighing 700 kg. Includes fuel consumption.
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RoW}| transport, freight,	7	tkm	Transport cobs to prep yard. Transport cobs to gasification facility.

lorry 3.5-7.5 metric ton, EURO6 | Alloc Def, U			
Maize cobs	6.5	ton	Input to gasification process
Bale loading {GLO}| market for | Alloc Def, U	22	p	
Electricity/heat			
Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Alloc Def, U	65	GJ	Heat required in the gasification process.
Electricity, low voltage {ZA}| market for | Alloc Def, U	32.75721	MWh	Electricity used for irrigation: powering of pump for the entire season.

3.2.2 Impact categories considered for this study

To comply with the goal of the study and ensure that the uncertainties are limited, the midpoint level impact indicators of the ReCiPe method are used. The impact categories are given in Table 3.20, adapted from Goedkoop *et al* (2013).

Table 3.20 Overview of midpoint categories, indicators and characterization factors

IMPACT CATEGORY		**INDICATOR**		**CHARACTERIZATION FACTOR**	
Name	**Abbr.**	**Name**	**Unit**	**Name**	**Unit**
climate change	CC	infra-red radiative forcing	W.yr/m^2	global warming potential	kg (CO_2 to air)
ozone depletion	OD	Stratospheric ozone concentration	ppt.yr	ozone depletion potential	kg (CFC-11 to air)
terrestrial acidification	TA	base saturation	yr.m^2	terrestrial acidification potential	kg (SO_2 to air)

freshwater eutrophication	FE	phosphorus concentration	yr.kg/m^3	freshwater eutrophication potential	kg (P to freshwater)
marine eutrophication	ME	nitrogen concentration	yr.kg/m^3	marine eutrophication potential	kg (N to freshwater)
human toxicity	HT	hazard-weighted dose	–	human toxicity potential	kg (14DCB to urban air)
photochemical oxidant formation	POF	Photochemical ozone concentration	kg	photochemical oxidant formation potential	kg (NMVOC to air)
particulate matter formation	PMF	PM10 intake	kg	particulate matter formation potential	kg (PM_{10} to air)
terrestrial ecotoxicity	TET	hazard-weighted concentration	m^2.yr	terrestrial ecotoxicity potential	kg (14DCB to industrial soil)
freshwater ecotoxicity	FET	hazard-weighted concentration	m^2.yr	freshwater ecotoxicity potential	kg (14DCB to freshwater)
marine ecotoxicity	MET	hazard-weighted concentration	m^2.yr	marine ecotoxicity potential	kg (14-DCB to marine water)
ionising radiation	IR	absorbed dose	man.Sv	ionising radiation potential	kg (U235 to air)
agricultural land occupation	ALO	occupation	m^2.yr	agricultural land occupation potential	m^2.yr (agricultural land)
urban land occupation	ULO	occupation	m^2.yr	urban land occupation potential	m^2.yr (urban land)
natural land transformation	NLT	transformation	m^2	natural land transformation potential	m^2 (natural land)
mineral resource depletion	MRD	grade decrease	kg^{-1}	mineral depletion potential	kg (Fe)
fossil resource depletion	FD	lower heating value	MJ	fossil depletion potential	kg (oil)

3.3 Life cycle impact assessment

The impact results of the production of maize and extraction of maize cobs for use as feedstock for electricity generation are presented in this section. The basis or calculations and data inventory are discussed in detail in Sections 3.1 and 3.2. This section may be reviewed for better understanding of the impact assessment. The results presented in Table 3.21 below are based on the production of 1 kg of maize cobs. The results were calculated by the SimaPro program for the inputs and outputs that are modelled. The model is presented in Appendix 4.

Table 3.21 Impact assessment results for maize cob production route

IMPACT CATEGORY	UNIT	MAIZE COBS
Fossil depletion	kg (oil)	1.16×10^{-5}
Climate change (Human Health)	kg (CO_2 to air)	5.06×10^{-6}
Climate change (Ecosystems)	m^2.yr	3.20×10^{-6}
Particulate matter formation	kg (PM_{10} to air)	2.57×10^{-6}
Metal depletion	Kg (Fe)	2.14×10^{-6}
Human toxicity	kg (14DCB to urban air)	1.30×10^{-6}
Agricultural land occupation	m^2.yr (agricultural land)	4.83×10^{-7}
Urban land occupation	m^2.yr (urban land)	1.91×10^{-7}
Natural land transformation	m^2 (natural land)	1.07×10^{-7}
Terrestrial ecotoxicity	kg (14DCB to industrial soil)	2.04×10^{-8}
Terrestrial acidification	kg (SO_2 to air)	1.46×10^{-8}
Freshwater eutrophication	kg (P to freshwater)	9.97×10^{-9}
Ionising radiation	kg (U235 to air)	5.28×10^{-9}
Freshwater ecotoxicity	kg (14DCB to freshwater)	4.78×10^{-9}
Ozone depletion	kg (CFC-11 to air)	1.26×10^{-9}
Marine ecotoxicity	kg (14DCB to marine water)	9.44×10^{-10}
Photochemical oxidant formation	kg (NMVOC to air)	6.76×10^{-10}

The results presented represent industry practices for South Africa. Table 3.21 shows that the production of maize (agricultural practices), extraction of maize cobs and generation of electricity through gasification results in land transformation of 1.07×10^{-7} m^2 and agricultural land occupation of 4.83×10^{-7} m^2, in a year. Figure 3.2 shows the magnitude of each of the impact categories under study. The following section shows how each unit process contributes to the environmental impact results, as well as the major contributing processes in the entire life cycle.

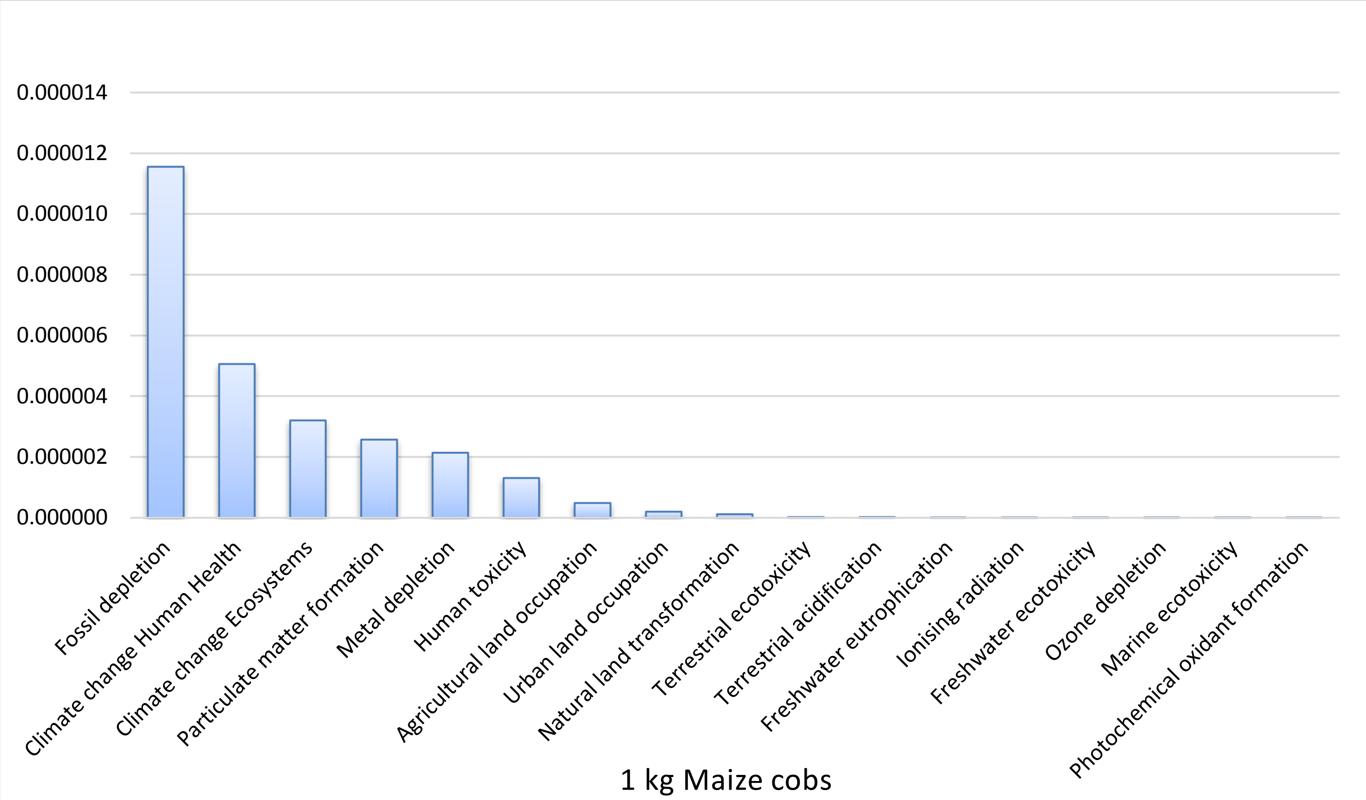

Figure 3.2 Normalization impact assessment results for production of 1 kg maize cobs

3.3.1 Contribution analysis

For the contribution analysis, the most significant impact categories (from Figure 3.2) are analysed, namely; fossil depletion, climate change (human health), climate change (ecosystem), particulate matter formation, metal depletion, human toxicity and agricultural and urban land occupation. The remaining impact category results are presented in Appendix 5.

3.3.1.1 Fossil depletion

This impact is a result of the use of fossil fuels, for example; coal and gas. They provide feedstock in the manufacturing of agricultural pesticides and fertilizers, and are therefore, important in this study. The characterization factor is measured in kg of oil equivalent.

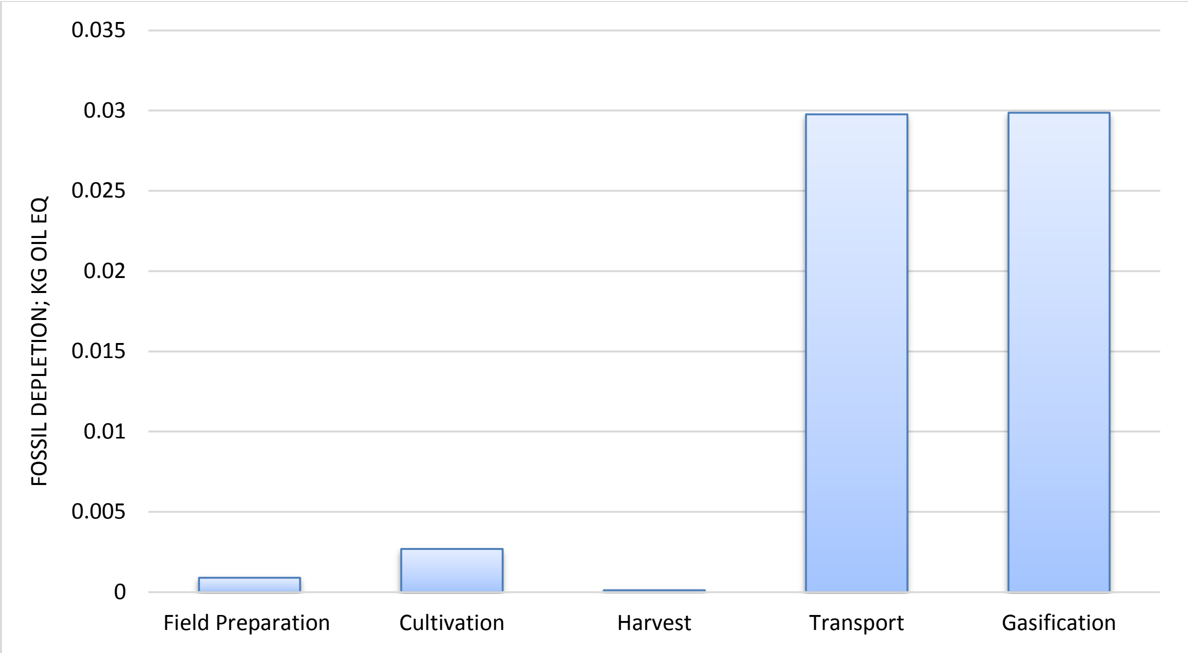

Figure 3.3 Contributions analysis of unit production processes to fossil depletion

It is deduced from Figure 3.3 that gasification and transport contribute about 47 % each to fossil depletion, while cultivation, field preparation and harvest contribute 4.2 %, 1.4 % and 0.2 % respectively. The major contributors to fossil depletion, as calculated in SimaPro are presented in Table 3.22, a node cut-off of 3 % was used.

Table 3.22 Major contributors to fossil depletion for production of 1 kg maize cobs

PROCESS	**MAIZE COBS (kg oil eq.)**
Total of all processes	3.57×10^{-3}
Remaining processes	1.10×10^{-3}
Hard coal {ZA}| mine operation	7.74×10^{-4}
Polyethylene, high density, granulate {RoW}| production	2.94×10^{-4}
Hard coal {CN}| mine operation	2.48×10^{-4}
Petroleum {RoW}| petroleum and gas production, on-shore	2.27×10^{-4}
Petroleum {RME}| production, onshore	2.24×10^{-4}
Lignite {RoW}| mine operation	1.57×10^{-4}
Hard coal {RNA}| mine operation	1.48×10^{-4}
Polyethylene, high density, granulate {RER}| production	1.45×10^{-4}
Hard coal {RoW}| mine operation	1.41×10^{-4}
Natural gas, high pressure {RU}| natural gas production	1.08×10^{-4}

3.3.1.2 Climate change

This indicator measures the greenhouse gas emissions which have been generated by the system. It includes the production of materials, electricity during use, transportation and distribution, etc. Climate change is also known as Global Warming Potential (GWP) or the "carbon footprint" and is reported in kilograms (kg) of carbon dioxide-equivalents. GWP measures take into account all the emissions of GHGs, which include:

- Carbon dioxide (CO_2);
- Methane (CH_4);
- Nitrous oxide (N_2O);
- Chlorofluorocarbons (CFCs);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs); and
- Sulphur hexafluoride (SF_6)

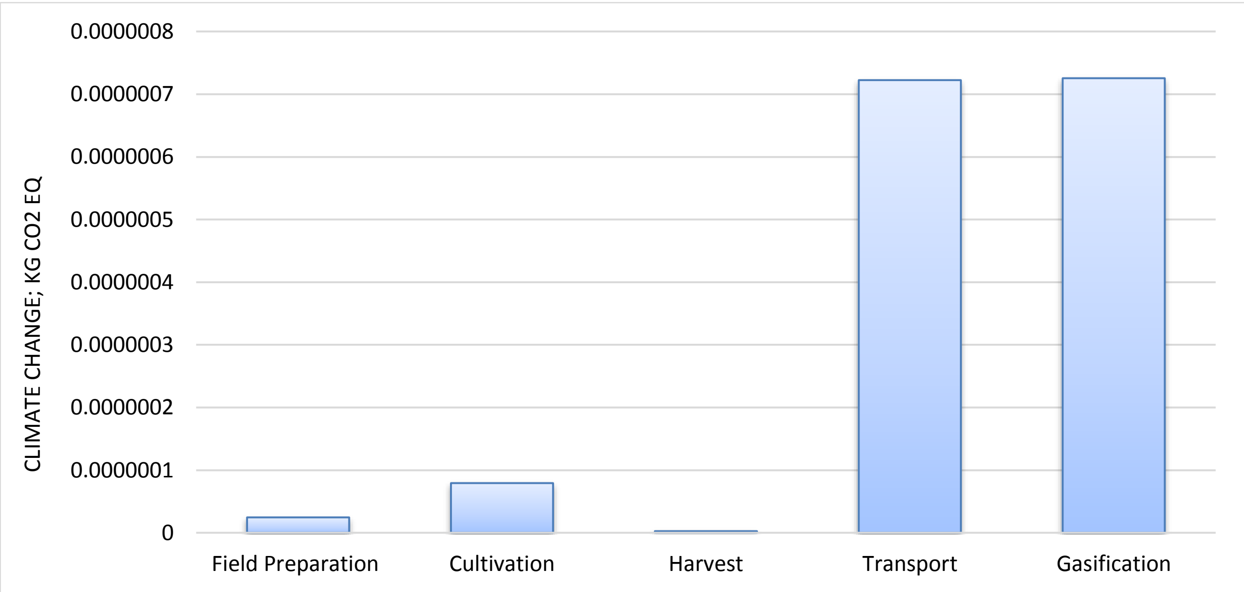

Figure 3.4 Contributions of unit processes to climate change (human health)

Derived from Figure 3.4, the contributions of each production unit process are represented in numbers as follows;

- Gasification contributes 46.7 %;
- Transport contributes 46.5 %;

- Cultivation contributes 5.1 %;
- Field preparation contributes 1.6 %; and
- Harvest contributes about 0.2 % to GWP.

In order to better understand these contributions, the major contributing processes (material, energy and fuel inputs) within the production route are given in the Tables 3.23 and 3.24.

Table 3.23 Major contributors to climate change (human health) for production of 1 kg maize cobs

PROCESS	**MAIZE COBS (kg CO_2 eq)**
Total of all processes	1.02×10^{-7}
Remaining processes	6.99×10^{-8}
Electricity, high voltage {ZA}| electricity production, hard coal	2.46×10^{-8}
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	3.99×10^{-9}
Pig iron {GLO}| production	3.71×10^{-9}

Climate change (ecosystems) represents impacts on all living things in a specific area as well as the non-living things with which they interact, such as air, soil, water, and sunlight. The characterization factor is measured in m^2.yr. The contribution of the unit processes presented in the inventory are given in Figure 3.5.

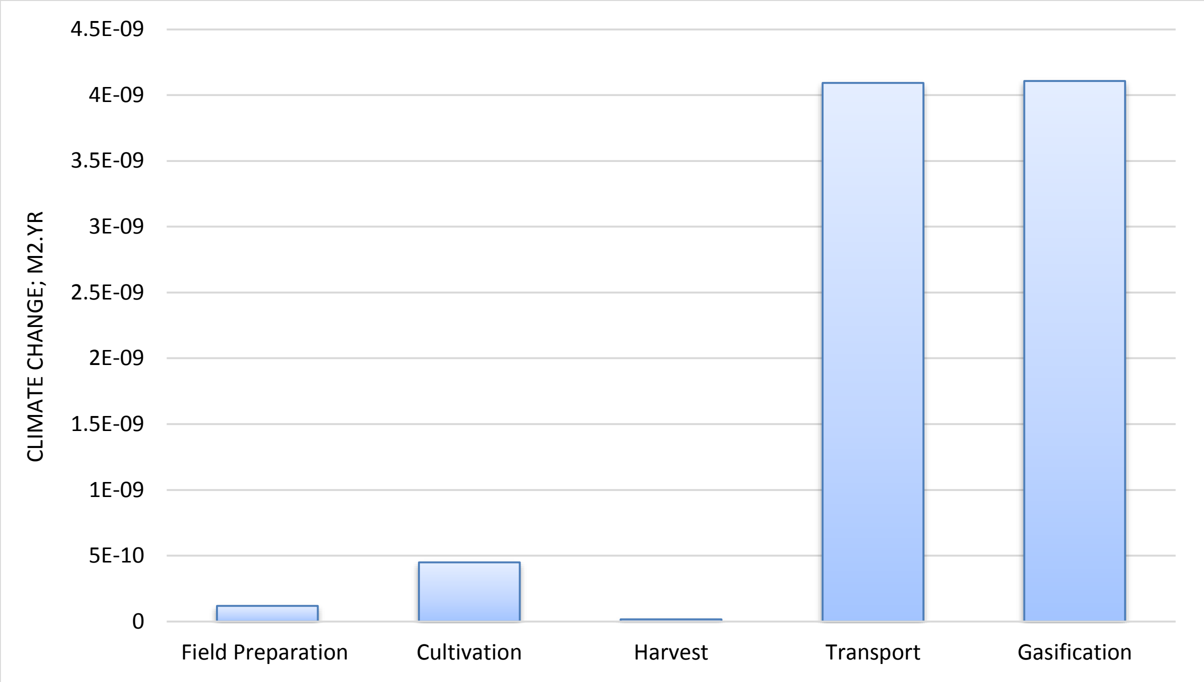

Figure 3.5 Contributions of unit processes to climate change (ecosystems)

Based on the graphical representation of the contribution results in Figure 3.5, gasification and transport contribute close to 47 % each, while cultivation contributes just over 5 %, field preparation and harvest contribute about 1 % and 0.2 % respectively, to climate change effects on the ecosystem.

Table 3.24 Major contributors to climate change (ecosystems) for production of 1 kg maize cobs

PROCESS	**MAIZE COBS (m^2.yr)**
Total of all processes	5.79×10^{-10}
Remaining processes	3.96×10^{-10}
Electricity, high voltage {ZA}| electricity production, hard coal	1.40×10^{-10}
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	2.26×10^{-11}
Pig iron {GLO}| production	2.10×10^{-11}

3.3.1.3 Particulate matter formation

The source and impact trail of particulate matter formation starts with an emission of NO_x, NH_3, SO_2, or primary $PM_{2.5}$ to the atmosphere, followed by atmospheric fate and chemistry in the air; NO_x, NH_3, and SO_2 are transformed in air to secondary aerosols (Van Zelm *et al*, 2016). The characterization factor of particulate matter formation is the intake fraction of PM_{10}. The unit is kg PM_{10} equivalents.

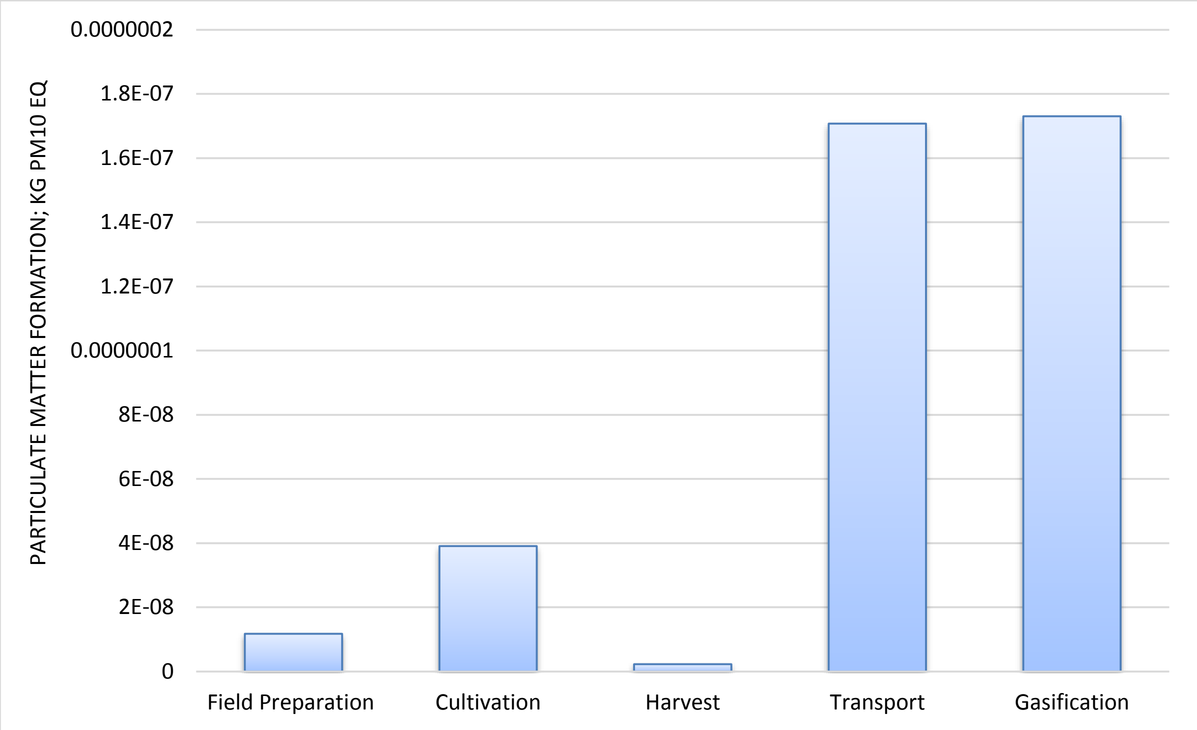

Figure 3.6 Contributions of unit processes to particulate matter formation

It can be seen in Figure 3.6 that gasification contributes 1.73×10^{-7} kg of PM_{10} equivalents which accounts for 44 % of the particulate matter formation, transport accounts for 43 % of the emissions with a contribution of 1.71×10^{-7} kg of PM_{10} equivalents. Cultivation contributes close to 10 %, while field preparation and harvest account for just over 3 % of the particulate matter formation. The major contributors to particulate matter formation are presented in Table 3.25.

Table 3.25 Major contributors to particulate matter formation for production of 1 kg maize cobs

PROCESS	MAIZE COBS (kg PM_{10} eq)
Total of all processes	5.20×10^{-8}
Remaining processes	3.23×10^{-8}
Electricity, high voltage {ZA}| electricity production, hard coal	1.07×10^{-8}
Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe	3.21×10^{-9}
Electricity, high voltage {IN}| electricity production, lignite	2.17×10^{-9}
Electricity, high voltage {RFC}| electricity production, lignite	1.82×10^{-9}
Electricity, high voltage {SERC}| electricity production, lignite	1.58×10^{-9}

3.3.1.4 Metal depletion

Natural resources are usually divided into non-renewable and renewable resources. The consumption of these resources beyond their rate of replenishment is known as resource depletion. Resource depletion is very common in farming, mining, water use and fuel consumption (Library Index, 2017), making its analysis and understanding important for this study. The characterization factor for metal depletion is the decrease in grade. The unit is kg Iron (Fe) equivalents. Figure 3.7 shows how each of the unit processes in the maize cob production chain contribute towards metal depletion.

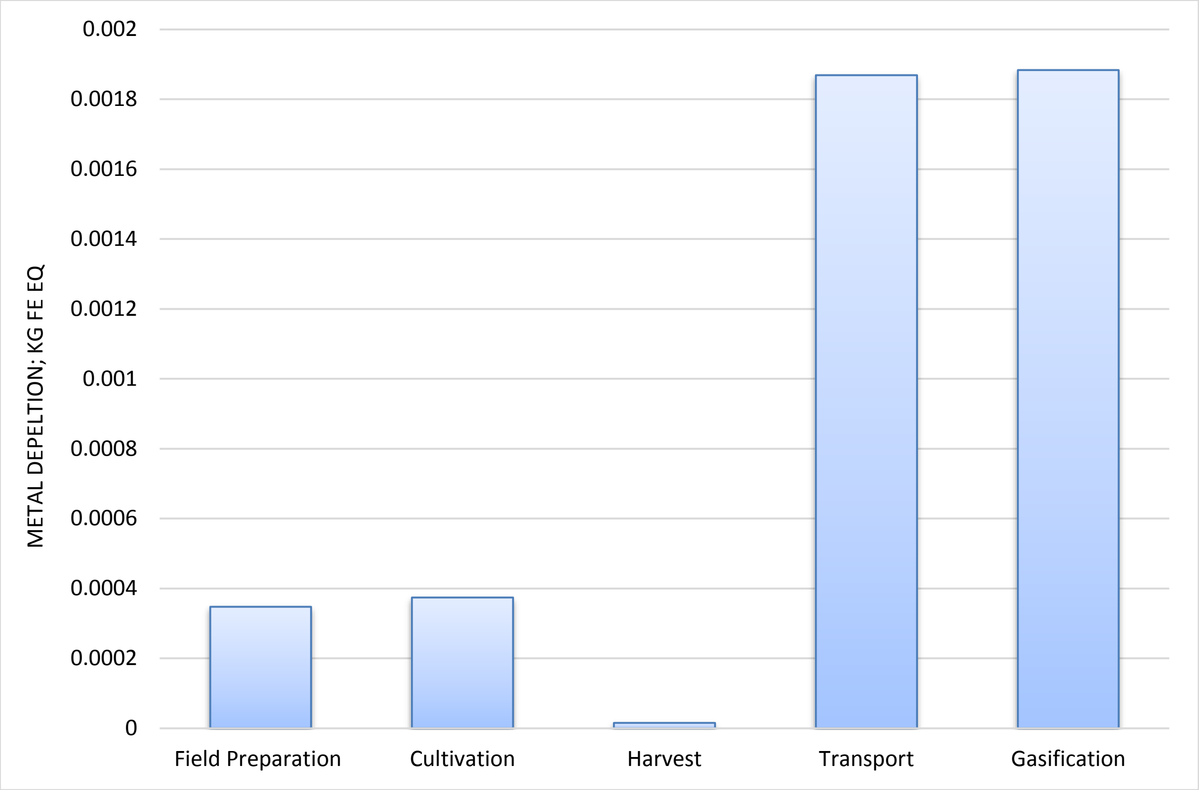

Figure 3.7 Contributions of unit processes to metal depletion

Derived from Figure 3.7, the contributions of each unit process in the maize cob production route are represented in numbers as follows;

- Gasification contributes nearly 42 %;
- Transport contributes 41.6 %;
- Cultivation contributes 8.3 %;
- Field preparation contributes 7.7 %; and
- Harvest contributes about 4 % to MRD.

The major contributors to metal depletion are given in Table 3.26.

Table 3.26 Major contributors to metal depletion for production of 1 kg maize cobs

PROCESS	**MAIZE COBS (kg Fe eq)**
Total of all processes	6.61×10^{-4}
Remaining processes	9.81×10^{-5}
Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Alloc Def, U	2.83×10^{-4}
Chromite ore concentrate {GLO}| production | Alloc Def, U	9.52×10^{-5}
Ferronickel, 25% Ni {GLO}| production | Alloc Def, U	4.33×10^{-5}
Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Alloc Def, U	3.51×10^{-5}
Manganese concentrate {GLO}| production | Alloc Def, U	3.20×10^{-5}
Copper concentrate {RAS}| copper mine operation | Alloc Def, U	2.81×10^{-5}
Copper concentrate {RoW}| copper mine operation | Alloc Def, U	2.40×10^{-5}
Copper concentrate {RLA}| copper mine operation | Alloc Def, U	2.18×10^{-5}

3.3.1.5 Human toxicity

The emission of some substances can have negative effects on human health. Assessments of toxicity are based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity (Green Guide, 2016). The characterization factor of human toxicity accounts for the environmental persistence and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical (Li *et al*, 2016). The unit is a kg of 1,4-dichlorobenzeen (14DCB) equivalent. The contributions of each unit process are quantified below.

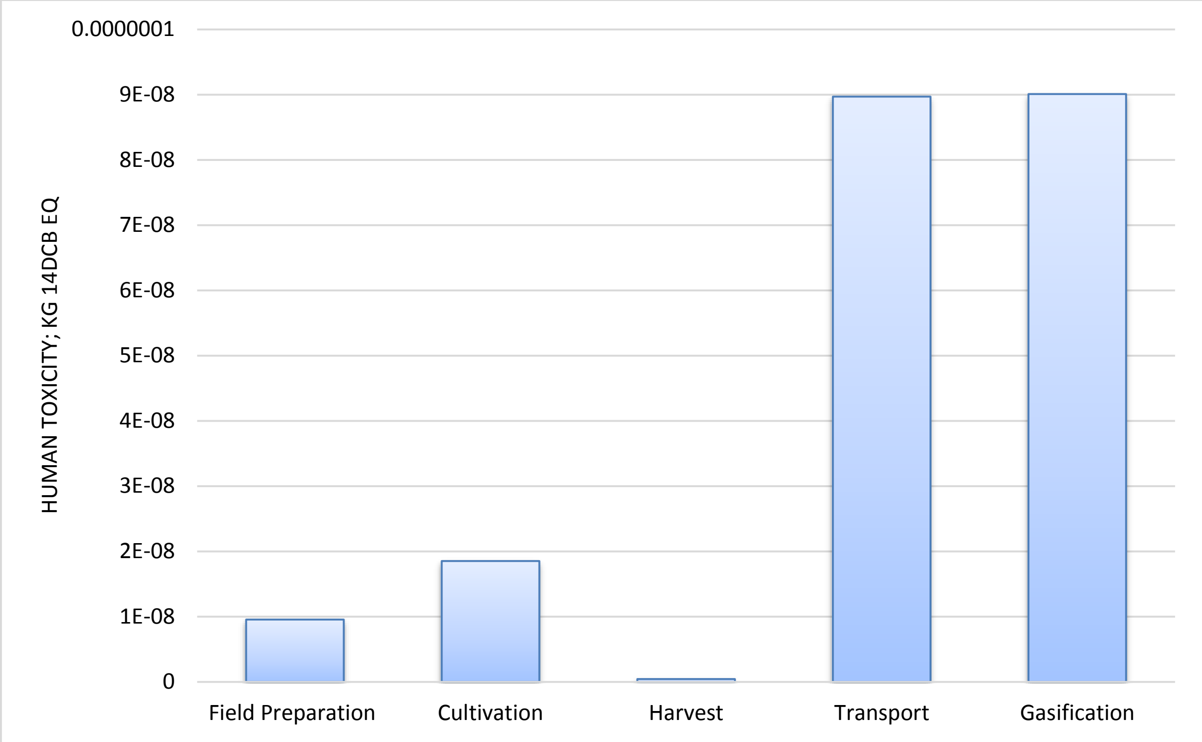

Figure 3.8 Contributions of unit processes to human toxicity

Figure 3.8 shows that both gasification and transport contribute just over 43% each to human toxicity. Cultivation contributes 8.9%, while field preparation and harvest contribute 4.6% and 0.1%, respectively, to human toxicity. The major contributors are given in Table 3.27;

Table 3.27 Major contributors to human toxicity for production of 1 kg maize cobs

PROCESS	**MAIZE COBS (kg 14DCB eq)**
Total of all processes	2.63×10^{-8}
Remaining processes	5.89×10^{-9}
Spoil from hard coal mining {GLO}| treatment of, in surface landfill	7.98×10^{-9}
Sulfidic tailing, off-site {GLO}| treatment of	7.55×10^{-9}
Spoil from lignite mining {GLO}| treatment of, in surface landfill	4.89×10^{-9}

3.3.1.6 Agricultural land occupation

This indicator represents the amount of agricultural land occupied for a specific period of time, usually a year. The unit is m^2.yr. The impact results for each unit process are presented graphically in Figure 3.9.

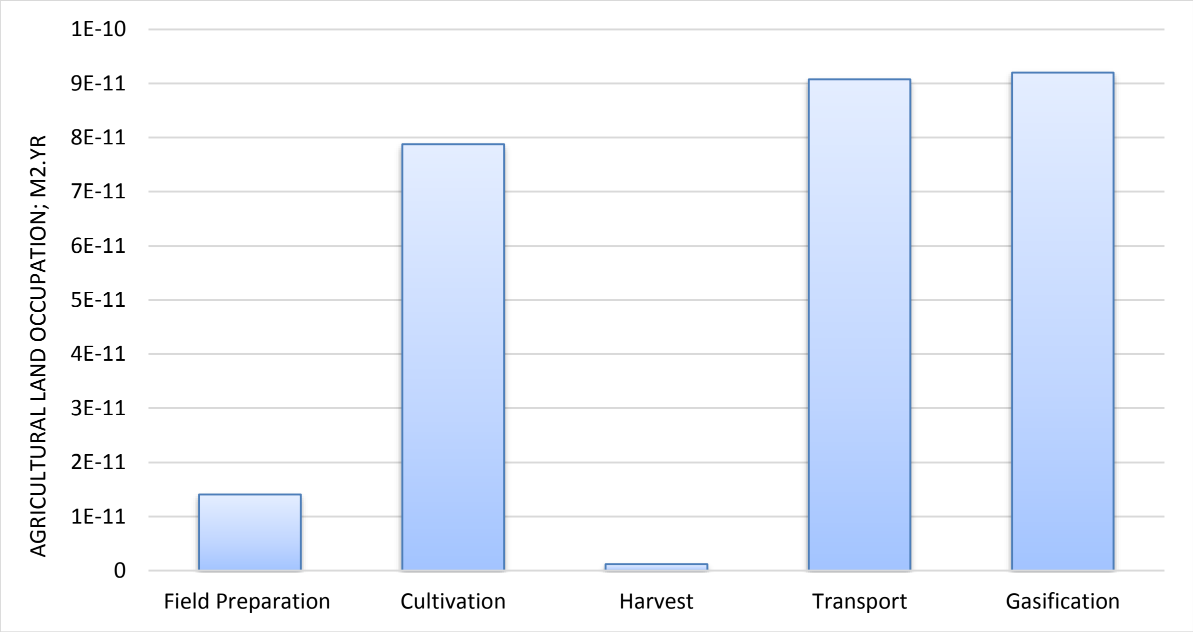

Figure 3.9 Contributions of unit processes to agricultural land occupation

The production of 1 kg maize cobs for electricity generation results in agricultural occupation of 9.2×10^{-11} m^2 in a year during the gasification process. Derived from Figure 3.9, the contributions of each unit process in the maize cob production route are represented in numbers as follows;

- Gasification contributes nearly 32.8 %;
- Transport contributes 33.2 %;
- Cultivation contributes 28.5 %;
- Field preparation contributes 5.1 %; and
- Harvest contributes 0.4 % to Agricultural Land Occupation.

Table 3.28 Major contributors to agricultural land occupation for production of 1 kg maize cobs

PROCESS	MAIZE COBS (m^2.yr)
Total of all processes	8.73×10^{-11}
Remaining processes	2.25×10^{-11}
Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management	1.76×10^{-11}
Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, spruce, sustainable forest management	1.70×10^{-11}
Maize seed, at farm {GLO}| production	8.64×10^{-12}
Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}| softwood forestry, mixed species, boreal forest	7.37×10^{-12}
Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management	4.24×10^{-12}
Sawlog and veneer log, hardwood, measured as solid wood under bark {DE}| hardwood forestry, beech, sustainable forest management	3.67×10^{-12}
Wood chips, wet, measured as dry mass {RoW}| softwood forestry, pine, sustainable forest management	3.21×10^{-12}
Wood chips, wet, measured as dry mass {RoW}| softwood forestry, spruce, sustainable forest management	3.11×10^{-12}

3.4 Life cycle interpretation

The results shown in Figure 3.10 indicate that the areas of concern in production of maize cobs for use as energy feedstock in electricity production affects fossil depletion, climate change, particulate matter formation, human toxicity and land occupation. These impacts are mainly as a result of the transportation and gasification stages of the production process. Gasification involves the removal of moisture content and devolatilization, as well as reaction with oxygen at high temperature. To achieve this, considerable amounts of energy use is required.

Table 3.22 shows that the acquisition (and use) of hard coal is a major contributor to fossil depletion. This can be attributed to the energy used during drying and combustion of maize cobs in the gasification process as well as the electricity required for the operation of the irrigation system. Petroleum and polyethylene were also shown as high contributors to fossil depletion, which can be due to the use of diesel in agricultural machinery, particularly tractors, and irrigation. The effect of natural gas production on fossil depletion can be attributed, mostly but not limited to, the gasification process.

The environmental impacts of the cultivation, field preparation and harvest are assumed to be due to the use of diesel for agricultural machinery (tractors, lime sprayers, fertilizer spreaders and harvesters), the use of material inputs (chemical plant protection, fertilizers) and irrigation. The global warming potential results are attributed to the use of heat in the gasification process, electricity - mainly for irrigation in the cultivation process, and the use (and production) of organic fertilizers. The relatively high particulate matter formation results are considered to be due to the acquisition of coal and use of electricity mainly in irrigation.

The mineral resources depleted (shown in Table 3.26) are due to the use of irrigation infrastructure and tractors. These impacts are also due to the use of fertilizers and chemical plant protection. The use of tractors in the field preparation, cultivation and harvest stages of the life cycle result in the depletion of copper, irrigation results in the depletion of iron ore, while application of fertilizers and chemical plant protection depletes ferronickel, chromite ore and manganese.

The major contributing products to human toxicity are mainly due to coal mining for use in electricity production; which is required for irrigation (in cultivation) and heat addition (in gasification). The effects of agricultural land occupation are considerably high for cultivation, as it was initially anticipated. This is due to the large area of agricultural land required to grow maize with the intension of collecting maize cobs for electricity generation. Maize cobs have very low density compared to other energy feedstocks and would consequently occupy more land. The major contributors towards this impact category, given in Table 3.27 are maize seeds (required for cultivation) and the conversion of grassland into arable land.

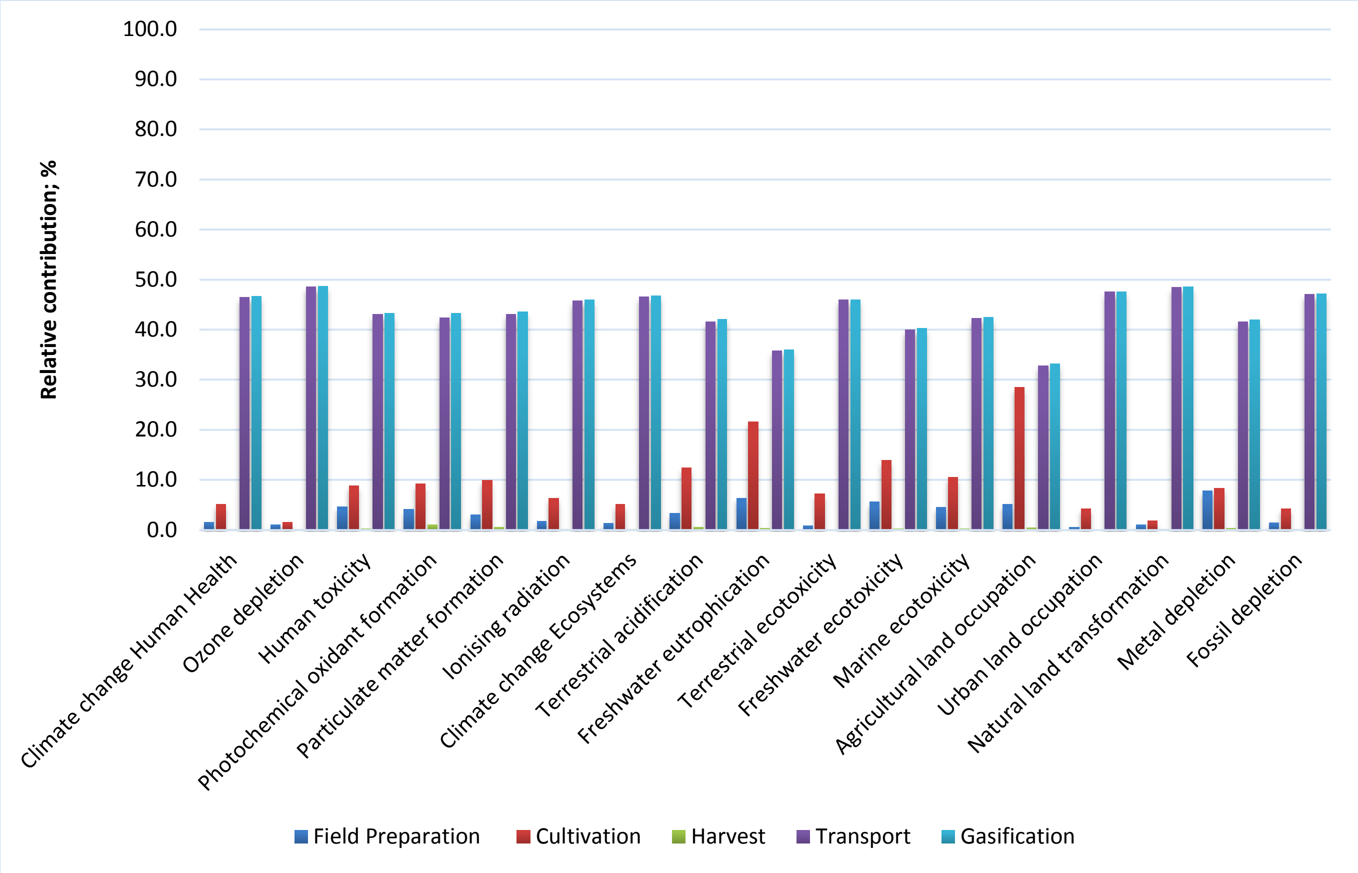

Figure 3.10 Relative contributions of unit processes associated with maize cobs production

The results show that transport and gasification contribute the most to all impact categories, however the major contributing materials are mostly associated with agricultural practices in maize production (i.e. machinery and tractor use, irrigation, fertilizer application and chemical plant protection). The relatively high impact results for the transport and gasification processes may be due to the diesel consumption in transportation and the fact that transport also includes the tractor-and-trailer systems that are used in the farm, as well as the large amount of energy required to convert maize cobs into synthetic gas and use of this gas for generation of electricity.

This could also be due to the fact that the process of gasification results in the release of by-products into the air (dust, ash and gases) which affect the environment and human health. The producer gas in biomass gasification requires cleaning before use, the process generates a large amount of liquid effluents (Mishra *et al*, 2015). Warneck (2002) and Plasinski *et al* (2007) recommend that gasification should release less than 1 g/m^3 of tar, however according to Rabou (2004) and Tchapda and Pisupati (2014), the biomass gasification process generates between 0.5 and 150 g/m^3 of tar. The effects of tar on the environment and human health are shown in Table 3.29.

Table 3.29 Health and environmental effects associated with selected aromatic hydrocarbons (tar)

AROMATIC HYDROCARBON	EFFECTS OF HUMAN HEALTH	EFFECT ON ENVIRONMENT
Naphthalene (Tertiary tar)	Haemolytic anaemia, haemolysis	Depletion of pulmonary glutathione and dose-dependent bronchiolar epithelial cell necrosis
Benzene (Secondary/tertiary tar)	Anaemia, drowsiness, dizziness, headaches, tremors, confusion	Benzene in soil or water decomposes with the presence of oxygen, contaminate groundwater
Toluene (Secondary tar)	Headaches to intoxication, convulsions, narcosis, and death	Toxic to both fish and other small organisms
Xylene (Secondary tar)	Irritation of the skin, eyes, nose, and throat, difficulty in breathing, headache, lack of muscle coordination, dizziness, confusion	Bio accumulate, in fish, high acute toxicity to aquatic life
Ethyl benzene (Secondary/tertiary tar)	Paralysis, trouble breathing, liver damage and death, drinking water contaminated	High acute toxicity to aquatic life causing death of animals, birds, or fish

Source: Mishra et al (2016)

According to EPA (1996), the high environment impacts associated with transportation may be due to the following activities which affect the environment (shown in Table 3.30):

Table 3.30 Summary of possible environmental impacts associated with road transport

AIR	WATER RESOURCES	LAND RESOURCES
Engine and evaporative emissions of CO, HC, NO_x, PM and lead	Surface and groundwater pollution form runoff (lubricants, coolants, vehicle deposits, road salt)	Land used for infrastructure
Emissions of CO_2 from fossil fuel combustion	Modification of water systems from road building	Extraction of road building materials. Abandoned rubble from road works
CFCs released during vehicle manufacture and disposal		Waste oil, tires and batteries
		Road vehicles withdrawn from service

Source: EPA (1996)

So, when the impacts associated with transportation and gasification are added up, they outweigh those of other unit processes, even though most major contributors are associated with other unit processes, particularly cultivation and field preparation.

4. COMPARATIVE LIFE CYCLE ASSESSMENT

The goal of the study includes the comparison of the maize cob production system with production of wheat and extraction of wheat stalks for generation of electricity using a fluidized bed gasifier, and extraction of coal for generation of electricity using the conventional method in South Africa. It is not the intention of this study to perform an in-depth life cycle assessment of the two systems, as these are mainly for comparison. However, due to the scarcity of similar studies in South Africa and lack of geographically representative data in the SimaPro software, it was necessary to input data to the program.

4.1 Wheat stalks life cycle inventory

For the purpose of this report, the words “stalks” and “straw” will be used interchangeably. It is assumed that land is transformed from grassland to agricultural land. The same amount of wheat stalks is required as feedstock to the gasification process (i.e. 6.5 tonnes) to produce 1 kWh of electricity. To ensure that the data is more representative and comparable to the system under study, it is assumed that irrigated wheat under conventional tillage is cultivated.

According to Agri SA (2017) the average yield of irrigated wheat grain in South Africa is 4.0 tonnes per hectare, with a market price of R3 100 per tonne. The unit processes for production of wheat stalks are field preparation, cultivation, harvest, transport and gasification.

A study conducted by Campbell *et al* (1991) indicates that the incorporation of wheat straw tended to increase soil organic N and soil organic C slightly. Soil organic N was depleted when straw was removed, however, soil organic C was unaffected. The study attributes this to a suggestion that in *situ* C from roots contribute more to the maintenance of soil organic matter than wheat straw.

Maize and wheat have different growing seasons with different environmental conditions, leading to dissimilarities in the fates of their residues. Wang *et al* (2015) suggests that because of this, residues derived from maize decompose faster than those of wheat. It is assumed in this study that the same amount of residue left on the ground during harvest would have a similar effect as of the base case with regards to ground cover and mulching. For the purpose of this study, it is assumed that 40 % of removal of wheat straw during cultivation.

Allocation between grain and straw was determined using the same method as the base case (maize cobs LCA). The economic value of the wheat stalks was first determined based on their nutritive or fertilizer value. For this, the following data were used;

Table 4.1 Economic value of wheat straw/stalks as energy feedstock

FERTILIZER	**CONTENT (kg/t)**	**ECONOMIC VALUE (R/kg)**	**MARKET PRICE (R/t)**
N	5.9	7.79	45.96
P_2O_5	2.09	18.20	38.04
K_2O	13.97	23.50	326.65
Total economic value of wheat stalks			410.65
Reference	*Lentz and Lindsey (2016)*	*tradekey.com*	Calculated

The calculated allocation factors are 0.82 for grain and 0.18 for straw.

The following data is used in the life cycle inventory, based on Pineo (2017);

For every 1.5 tonnes of wheat grain produced, 2.5 tonnes of stalks/straw can be obtained. Based on the straw yield, a total of 2.6 hectares is required to produce 6.5 tonnes of wheat stalks. The following inputs are required for the production of wheat per hectare;

Table 4.2 Primary data and material inputs for wheat stalk production system

INPUT	**QUANTITY**
Fuel consumption (tillage)	250 kWh
Seeds	0.16 kg
Lime	200 kg
NPK Fertilizer • N fertilizer source	 100 kg

• P fertilizer source • K fertilizer source	12 kg 34 kg
Chemical plant protection • Fungicide (Captan) • Herbicide (Glyphosate 240SL)	 0.5 kg 3 kg
Chemical spraying	250 kWh
Irrigation	510 m^3/t
Sulphur	5 kg

For transport, the wheat stalks are first transported by a tractor and trailer system and offloaded to a 7-tonne truck, which then transports them to the biomass preparation site and electricity generation facility. The grain is transported to a silo on the farm using a similar tractor and trailer system. The transport distances and inputs to the gasification process are assumed to be the same as those of the maize cob system.

4.1.1 Comparative analysis of maize cobs, maize stover and wheat stalks systems

The production of maize and extraction of maize cobs for electricity generation system was compared to the production of alternative biomass feedstocks for electricity production (i.e. maize stover and wheat stalks). For comparison, all three systems provide a function of 1 kg of biomass produced as feedstock for electricity generation through gasification. The results show that all the systems under comparison contribute more significantly towards fossil depletion, climate change, particulate matter formation, metal depletion, human toxicity and agricultural land occupation than the other impact categories considered in the study, as shown in Figure 4.1.

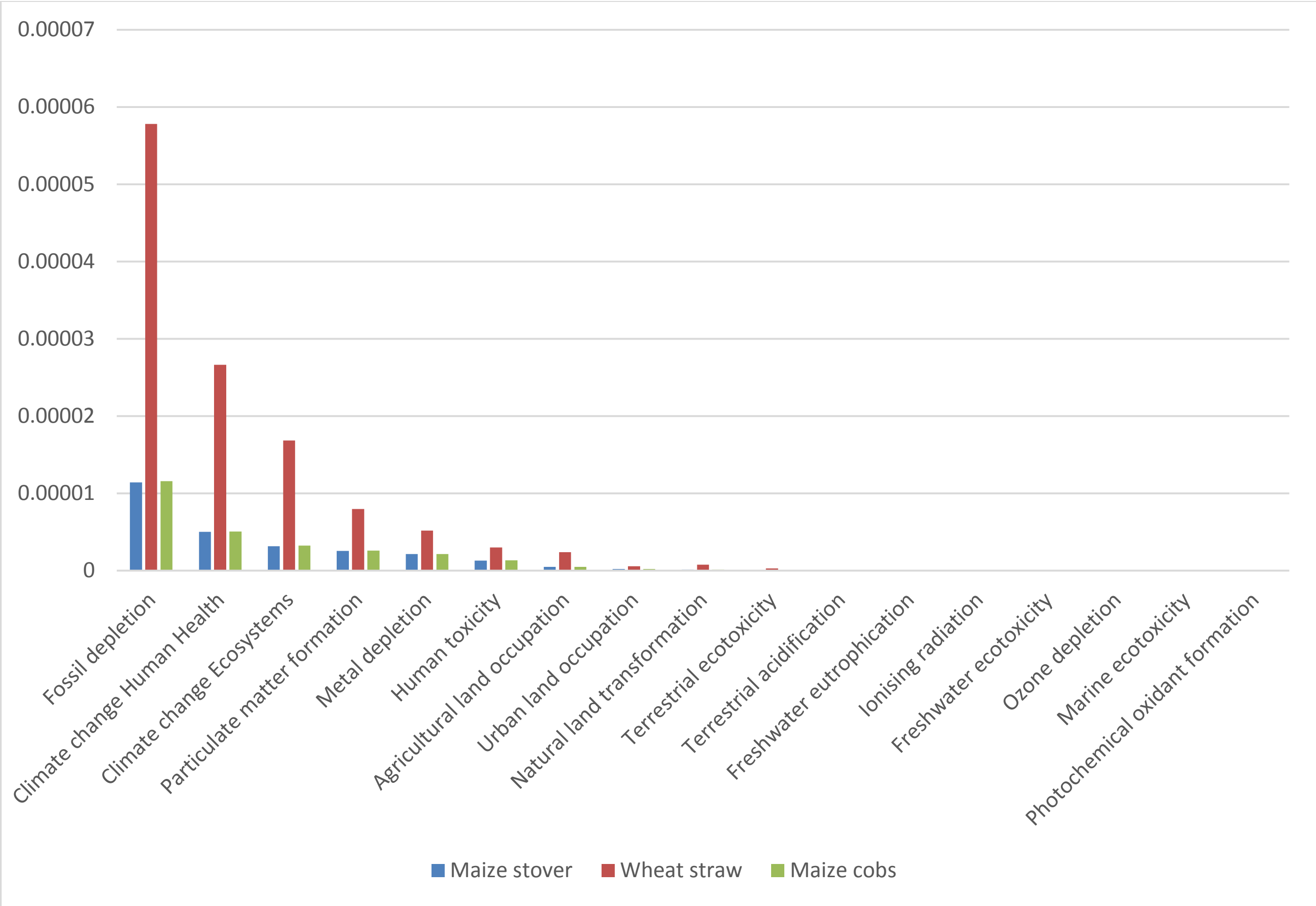

Figure 4.1 Maize cobs vs maize stover vs wheat straw – Normalization impact results

The results also show that the wheat stalks production system contributes more towards all environmental impacts (see Figure 4.1 and Table 4.3) than the maize stover and cobs systems. It is interesting to observe that this is so despite the fact that less agricultural land is required for the cultivation of wheat and it is required in relatively smaller mass as energy feedstock. It is shown in Table 4.3 that the agricultural land occupation results for maize cobs, maize stover and wheat straw are 4.83×10^{-7}, 4.76×10^{-7} and 2.38×10^{-6} m^2 respectively, in one year. The results in Table 4.3 show that a similar trend is followed for the other impact categories.

Table 4.3 Comparison of maize cobs, maize stover and wheat straw/stalks

IMPACT CATEGORY	UNIT	MAIZE STOVER	WHEAT STRAW	MAIZE COBS
Fossil depletion	kg oil eq	1.14×10^{-5}	5.78×10^{-5}	1.16×10^{-5}
Climate change Human Health	kg CO_2 eq	4.99×10^{-6}	2.66×10^{-5}	5.06×10^{-6}
Climate change Ecosystems	m^2.yr	3.16×10^{-6}	1.68×10^{-5}	3.20×10^{-6}
Particulate matter formation	kg PM_{10} eq	2.54×10^{-6}	7.94×10^{-6}	2.57×10^{-6}
Metal depletion	kg Fe eq	2.11×10^{-6}	5.15×10^{-6}	2.14×10^{-6}
Human toxicity	kg 14DCB eq	1.28×10^{-6}	2.98×10^{-6}	1.30×10^{-6}
Agricultural land occupation	m^2.yr	4.76×10^{-7}	2.38×10^{-6}	4.83×10^{-7}
Urban land occupation	m^2.yr	1.89×10^{-7}	5.40×10^{-7}	1.91×10^{-7}
Natural land transformation	m^2	1.05×10^{-7}	7.34×10^{-7}	1.07×10^{-7}
Terrestrial ecotoxicity	kg 14DCB eq	2.01×10^{-8}	2.49×10^{-7}	2.04×10^{-8}
Terrestrial acidification	kg SO_2 eq	1.44×10^{-8}	4.64×10^{-8}	1.46×10^{-8}
Freshwater eutrophication	kg P eq	9.84×10^{-9}	1.89×10^{-8}	9.97×10^{-9}
Ionising radiation	kg U235 eq	5.21×10^{-9}	1.59×10^{-8}	5.28×10^{-9}
Freshwater ecotoxicity	kg 14DCB eq	4.71×10^{-9}	1.08×10^{-8}	4.78×10^{-9}
Ozone depletion	kg CFC-11 eq	1.24×10^{-9}	4.95×10^{-9}	1.26×10^{-9}
Marine ecotoxicity	kg 14DCB eq	9.32×10^{-10}	2.11×10^{-9}	9.44×10^{-10}
Photochemical oxidant formation	kg NMVOC eq	6.67×10^{-10}	2.31×10^{-9}	6.76×10^{-10}

It is shown in the results that the preparation of wheat stalks for electricity production results in higher environmental impacts than the production of maize cobs or stover. Also, maize cobs and stover are products of the same agricultural inputs and practices, however the impacts associated with maize cobs are higher than those of maize stover. Areas of concern in all production systems are fossil depletion, climate change, particulate matter formation, metal depletion, human toxicity and agricultural land occupation. To understand why wheat stalks impacts are higher than those of maize cobs and stover, it is important to understand how agricultural systems affect these impacts.

The environmental impacts of crop production are a result of various components which include, but are not limited to the ones outlined in Table 4.4.

Table 4.4 Potential impacts of crop production on components of the environment

ENVIRONMENTAL COMPONENT	POTENTIAL IMPACTS OF CROPPING
Land and water resources	Changes in land-use; forests, grasslands, wetlands, croplands (and use of marginal croplands), changes in use of water resources, mining of aquifers
Soils	Risks of soil degradation, erosion and salinization. Changes in soil conditions, structure, fertility, organic matter content, water holding capacity
Water quality	Pollution and eutrophication, nitrogen and phosphorus contamination of soils, water courses and water bodies. Pesticide, trace minerals and other residues contamination
Air	Changes in air quality, contribution to greenhouse gases (GHG) (methane and carbon dioxide). Pollution with pesticides
Human health	Changes in exposure to pests and diseases, exposure to agricultural chemicals and environmental pollutants

Source: FAO (1995)

Hendy *et al* (1995) reported that risk of pollution due to the use of fertilizer is greater for wheat than it is for maize. The wheat growing season is a little longer than that of maize, resulting in more water and agricultural inputs use. Furthermore, drip irrigation is usually used for maize, while sprinklers are more common for wheat cultivation. Drip irrigation results in less water loss due to evaporation or runoff. Thus, less water and electricity are used for irrigation of maize. The irrigation system for wheat usually results in increased runoff which may result in more water pollution and eutrophication.

4.2 Conventional system – Coal power

According to McKenzie (2012), Eskom uses about 1 kg of coal to produce 1 kWh of electricity. The SimaPro program contains two processes for electricity generation in South Africa. One is “mine operation” and includes land use during operation, emissions into water and air, water extraction during pumping, energy requirements for operation, explosives, as well as the deposition of spoil. This activity ends with 1 kg hard coal at the coal mine. The other process is electricity production and includes the reception of hard coal and operation of the power plant. This activity ends with 1kWh of high voltage electricity produced at the power plant.

It is assumed that the same type of transport as in the maize cob/stover and wheat stalks production system (i.e. 7 tonne truck) is used to transport the coal from the mine to the power plant. A transport distance of 10 km was assumed.

4.2.1 Comparative analysis of maize cobs and coal power systems

The production of maize and extraction of maize cobs for electricity generation system was compared to the conventional method of electricity generation in South Africa (i.e. coal power). The functional unit defined in Chapter 3 was used as a basis of comparison (i.e. production of 1 kWh of electricity). The results in Figure 4.2 show that the mining of coal and generation of electricity in a coal power plant in South Africa, contributes less towards agricultural land occupation and more towards all the other impact categories considered in this study, than the maize cobs system.

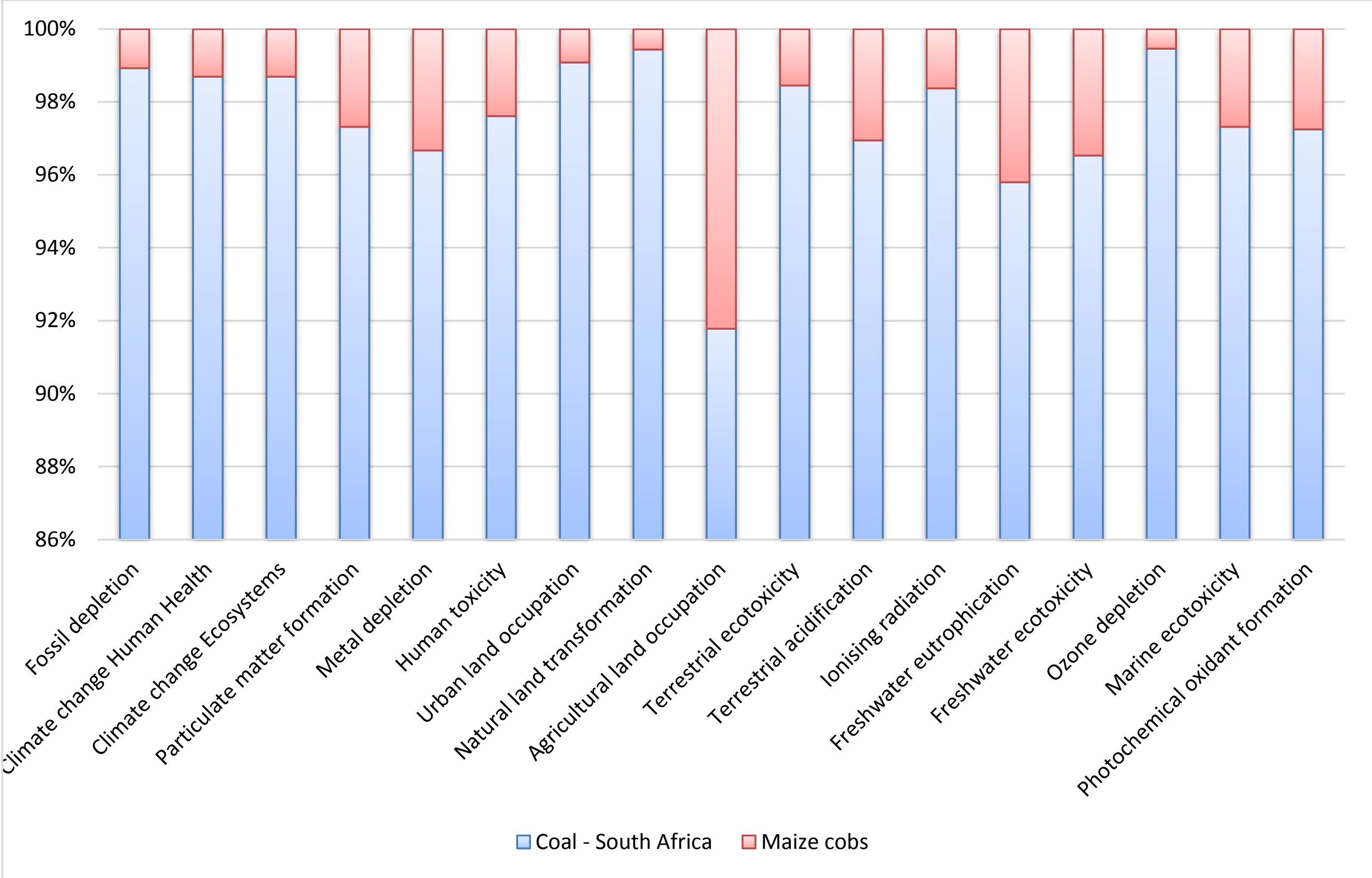

Figure 4.2 Maize cobs vs conventional system – relative contribution results

It is shown that the most significant impacts of using the conventional method of electricity generation are fossil depletion, ozone depletion, natural land transformation, urban land occupation and climate change, when compared to agricultural production and gasification of maize cobs. The impact results shown in Table 4.5 that coal power contributes 2 230 kg of oil equivalents while the maize cobs system contributes only 24 kg of oil equivalents. These results also indicate that urban land occupation, natural land transformation, climate change, ozone depletion and fossil depletion impacts are 99 % higher for coal power than the maize cobs system. Human toxicity, ionising radiation and terrestrial ecotoxicity impacts are 98 % higher, and the rest of the impacts are between 95 – 97 % higher for coal power compared to maize cobs.

Table 4.5 Comparison of maize cobs and coal for production of 1 kWh of electricity

IMPACT CATEGORY	UNIT	COAL - SOUTH AFRICA	MAIZE COBS
Fossil depletion	kg oil eq	2.23×10^{3}	2.42×10^{1}
Metal depletion	kg Fe eq	1.31×10^{2}	4.53×10^{0}
Climate change Human Health	kg CO_2 eq	5.24×10^{-2}	6.97×10^{-4}
Particulate matter formation	kg PM_{10} eq	1.27×10^{-2}	3.52×10^{-4}
Human toxicity	kg 14DCB eq	7.31×10^{-3}	1.79×10^{-4}
Climate change Ecosystems	m^2.yr	2.97×10^{-4}	3.95×10^{-6}
Ionising radiation	kg U235 eq	4.39×10^{-5}	7.27×10^{-7}
Urban land occupation	m^2.yr	2.56×10^{-5}	2.39×10^{-7}
Natural land transformation	m^2.yr	2.33×10^{-5}	1.32×10^{-7}
Ozone depletion	m^2	1.66×10^{-5}	8.99×10^{-8}
Agricultural land occupation	kg NMVOC eq	6.70×10^{-6}	6.01×10^{-7}
Photochemical oxidant formation	kg CFC-11 eq	3.29×10^{-6}	9.32×10^{-8}
Terrestrial ecotoxicity	kg 14DCB eq	1.58×10^{-6}	2.49×10^{-8}
Terrestrial acidification	kg SO_2 eq	5.62×10^{-7}	1.77×10^{-8}
Freshwater eutrophication	kg P eq	2.82×10^{-7}	1.24×10^{-8}
Freshwater ecotoxicity	kg 14DCB eq	1.64×10^{-7}	5.89×10^{-9}
Marine ecotoxicity	kg 14DCB eq	4.22×10^{-8}	1.17×10^{-9}

As expected, the maize cobs system contributes more towards agricultural land occupation and less towards natural land transformation and urban land occupation than the conventional method. Natural land transformation and urban land occupation results are higher for the conventional method, because large amounts of land are required for the mining of coal and construction of power plants.

The ozone depletion potential is considerably high for coal power while almost negligible for maize cobs system, because the mining and burning of coal results in emissions of chlorofluorocarbon (CFC) compounds and other halogenated hydrocarbons. The unit process that contributes most to ozone depletion is the burning of coal (electricity generation). Coal also contributes more towards climate change because CO, CH_4, CO_2 and N_2O are released during its life cycle. Again, the burning process contributes the most towards climate change, followed by the mining process. Transportation of coal from the mine to the power plant contributes considerably less towards GWP.

5. CONCLUSION AND RECOMMENDATIONS

The production of maize and extraction of maize cobs for electricity production has notable effects on depletion of fossil and mineral resources, formation of particulate matter, human toxicity and land transformation. The life cycle stages that contribute most towards environmental emissions are transportation and gasification. The production of the alternative energy crops considered in this study affect the same impact categories as the maize cobs system, but to a greater extent. The areas of concern with the conventional method of electricity production in South Africa are fossil and metal depletion, climate change, particulate matter formation, land occupation, human toxicity and ozone depletion. The impacts associated with coal power are over 90 % higher than those of the maize cobs system. It can therefore, be concluded that the maize cobs system has the lowest environmental impacts and is, as a result, environmentally better for electricity production.

It must be noted that due to the scarcity of data and lack of similar studies in South Africa, further research should be conducted on all the systems considered in this study. The recommendations for further research, particularly for the production of energy crops and related upstream processes in SA are highlighted below.

<u>Fertilization</u>

To ensure that fertilization is applied optimally, it is important to understand the fertilizer's uptake efficiency and soil properties (e.g. pH, acidity, structure and nutrient requirements). Soil sampling and testing should form an important part of agricultural production. To preserve water bodies, conserve the quality of soils and ecosystems, and for the benefit of human health; fertilizer application should be regulated and well-managed.

<u>Water use</u>

One of the biggest concerns for energy crops is water use. It is important to understand crop water need in great detail. Also, for drought-prone areas like South Africa, it is important to conserve aquifers and surface water. Although, crop-models (e.g. CROPWAT) were used to determine crop water requirements and irrigation requirements for this and other related studies; further studies should be conducted on water footprinting. Water footprint is an important indicator of sustainability as it quantifies and maps freshwater use.

Agricultural practices

Agricultural practices include tillage practices, soil quality improvement, water use and management of fertilizers and crop residue. Conservational tillage practices (minimum tillage or no till) may reduce environmental impacts such as fossil depletion, climate change and toxicity. Investigating the processes within the cultivation stage (e.g. irrigation) may address eutrophication and acidification. Growing of crops like maize and wheat in high rainfall areas may eliminate the need for irrigation and, in turn, address some environmental impacts.

Land transformation

Land transformation is an area of concern for policy makers. Further studies in South Africa should be conducted on direct and indirect land transformation as these affect biodiversity conservation, erosion control and forest management.

Biomass conversion technologies

The different types of biomass conversion technologies should be employed under relevant conditions. Intensive studies are required in the use of biomass for electricity generation. Detailed and informed designs of technologies like gasification, may increase the efficiency of these systems and reduce the emissions of harmful substances (particularly tar) to the environment.

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APPENDICES

Appendix 1: Crop water needs calculations

Crop water requirement, ET_C

It is the loss of water through transpiration of the growing plant plus evaporation from the soil.

$$
\begin{aligned}
ET_c &= K_c \times ET_o \\
&= 1.14 \times 8.70 \\
&= 9.92\ mm/day
\end{aligned}
$$

Leaching requirement ratio, LR

The leaching requirement is the minimum amount of irrigation water that is needed to pass through the root zone to control the salts within the tolerances of that particular cultivar, taking into consideration the quality of the water used.

$$
\begin{aligned}
LR &= \frac{EC_w}{5EC_e - EC_w} \\
&= \frac{155}{5(170) - 155} \\
&= 0.223
\end{aligned}
$$

Nett irrigation requirement, NIR

It is the depth of irrigation water necessary to meet crop water requirement.

$$
\begin{aligned}
NIR &= \frac{ET_c}{1 - LR} \\
&= \frac{9.92}{1 - 0.223} \\
&= 12.77\ mm/day
\end{aligned}
$$

Readily available water, RAW

This is the depth of soil water available within the effective root depth of the crop.

$$Available\ water, AW = WHC \times ERD$$
$$= 100 \times 0.6$$
$$= 60\ mm$$

$$RAW = AW \times \frac{\propto}{100}$$
$$= 60 \times \frac{55}{100}$$
$$= 33\ mm$$

Percentage wetted area, P_W

It is the average horizontal area wetted crop root zone depth in relation to the total cropped area. According to FAO (2002), the desirable P_w for widely spaced crops has a minimum of 33 % and maximum of 67 %. According to Keller and Bliesner (1990), P_w often approaches 100 % for closely spaced crops with rows and drip laterals spaced less than 1.8 m apart and according to FAO (2002), the area wetted by one emitter for sandy loam is 1 m^2.

$$A_w = \frac{\pi D^2}{4}$$
$$D = \sqrt{\frac{4A_w}{\pi}}$$
$$= 1.1\ m$$

$$P_w = \frac{100 \times N_d \times S_e \times D}{S_p \times S_e}$$
$$= \frac{100 \times 1 \times 0.3 \times 1.1}{1.5 \times 0.3}$$
$$= 73\ \%$$

Cycle length, t_c

The actual time lapse between beginning of two successive applications for a specific irrigation set.

$$t_c = \frac{RAW \times P_w}{NIR_d}$$
$$= \frac{33 \times 0.73}{12.77}$$
$$= 1.89\ days$$

Use the cycle length of 2 days.

Gross irrigation requirement per cycle, GIR_c

This figure is determined by incorporating system efficiency.

$$GIR_c = \frac{NIR}{\eta} \times t_c$$
$$= \frac{12.77}{0.95} \times 2$$
$$= 26.88\ mm$$

Stand time, t_s

It is the period for which a system has to irrigate to apply the design application. To calculate the application rate (also known as precipitation rate), divide the emitter flow rate (l/h) by area covered per emitter. The application rate will be based on the wetted strip.

$$AR = \frac{q_e}{D \times S_e}$$
$$= \frac{1.0}{1.1 \times 0.3}$$
$$= 3.03 \frac{l}{hr.m^2}$$

$$t_s = \frac{GIR_c}{AR}$$
$$= \frac{26.88}{3.03}$$
$$= 8.87\ hr$$

Theoretical size of irrigation group

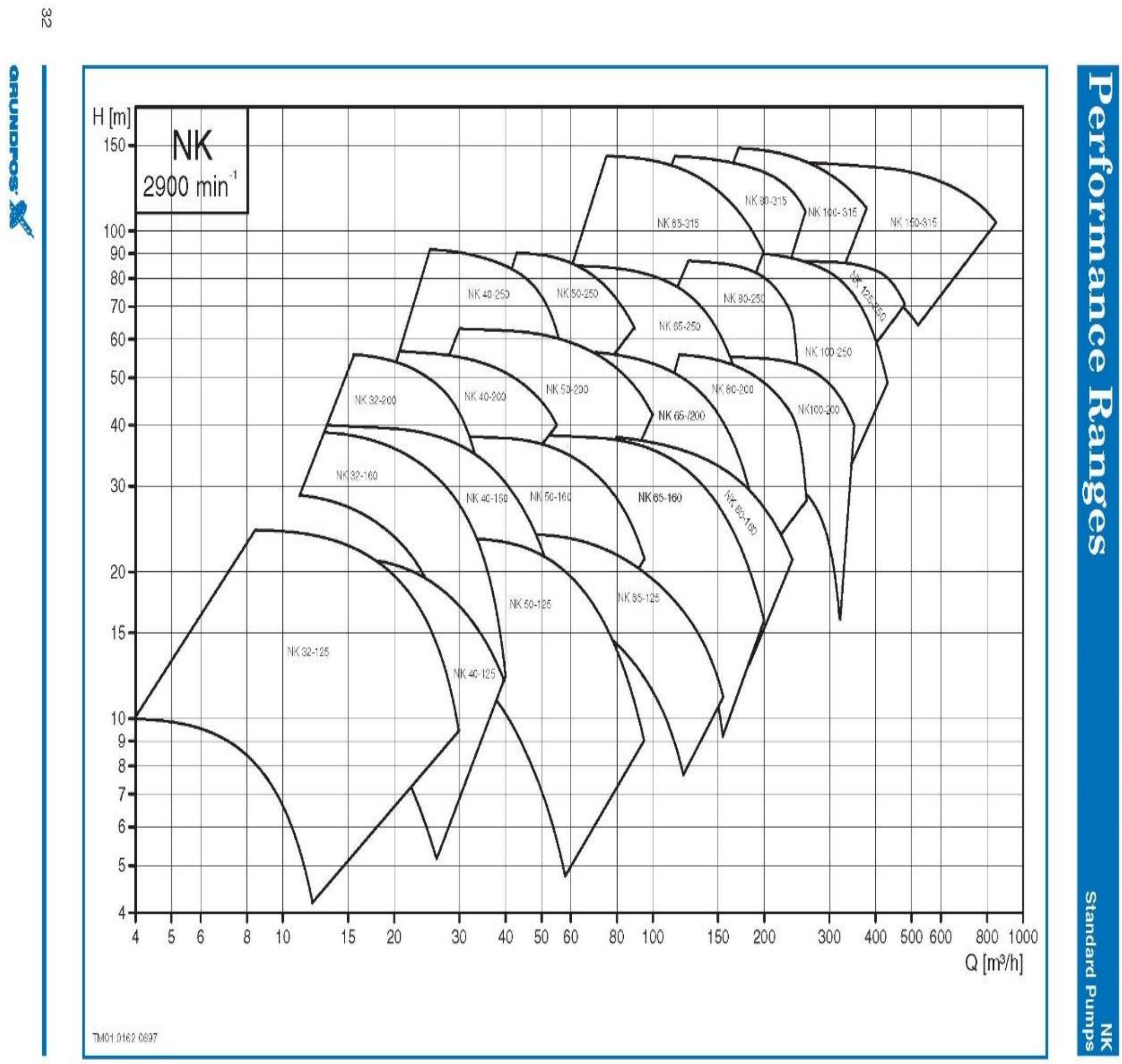
Operating hours per cycle (t) = t_s x t_c x shift number = 8.87 x 2 x 2 = 35.5 hrs, the system capacity is:

$$Q = \frac{GIR_C \times A_T \times 10}{t}$$
$$= \frac{26.88 \times 22 \times 10}{35.5}$$
$$= 166.6\, m^3/hr$$

It is assumed that the system applies 166.6 $m^3.hr^{-1}$ for about 9 hours, every 2 days, when the drippers are operating together. The system works for a total of 111 days during the season. The total amount of water required to irrigate the 22 hectares of maize for the entire period can then be determined as follows;

$$V_{total} = Q \times t_s \times no.of\ irrigation\ days$$
$$= 166.6 \times 9 \times 111$$
$$= 166\ 433.4\, m^3$$

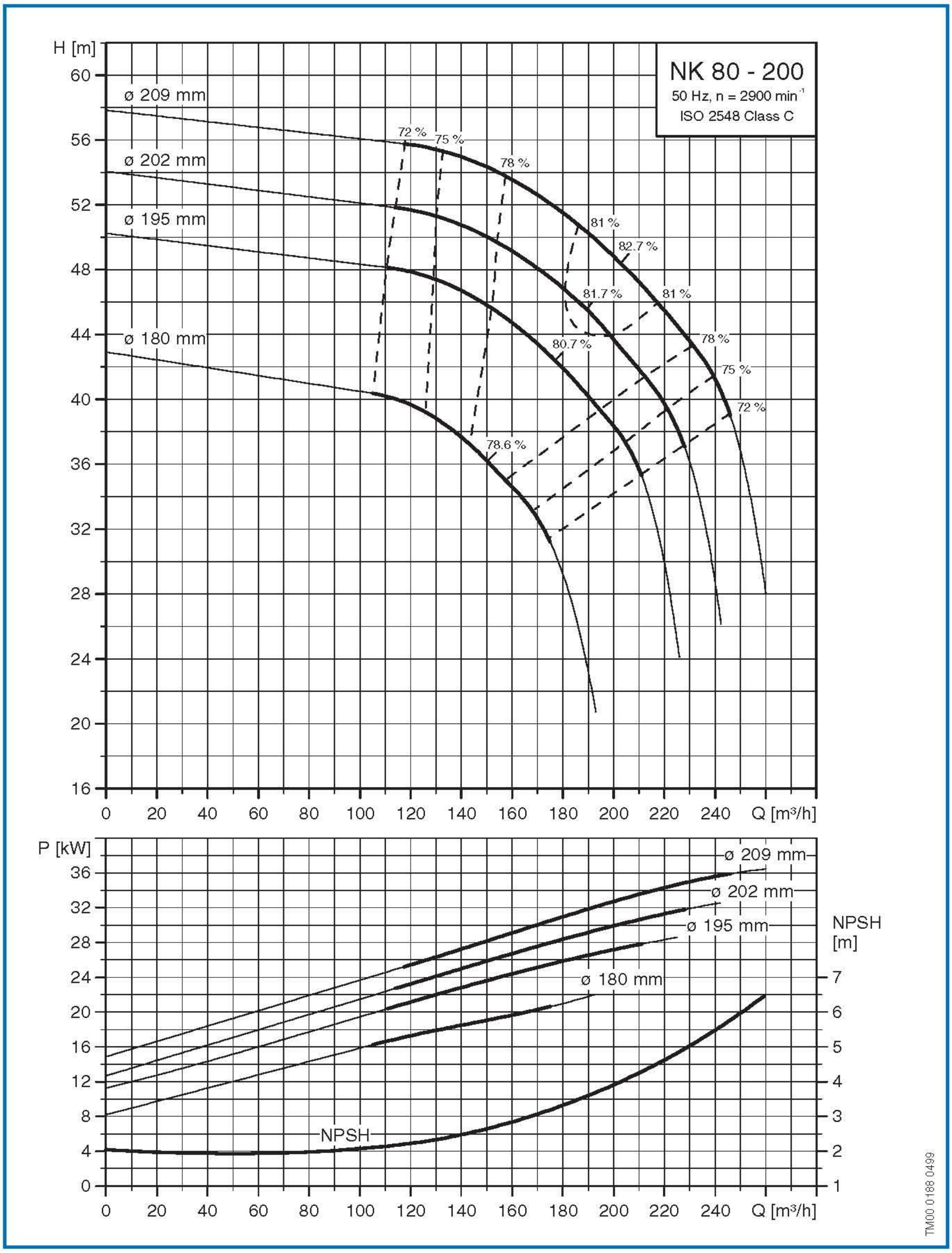
Appendix 2: Pump selection curve



Appendix 3: Pump performance curve

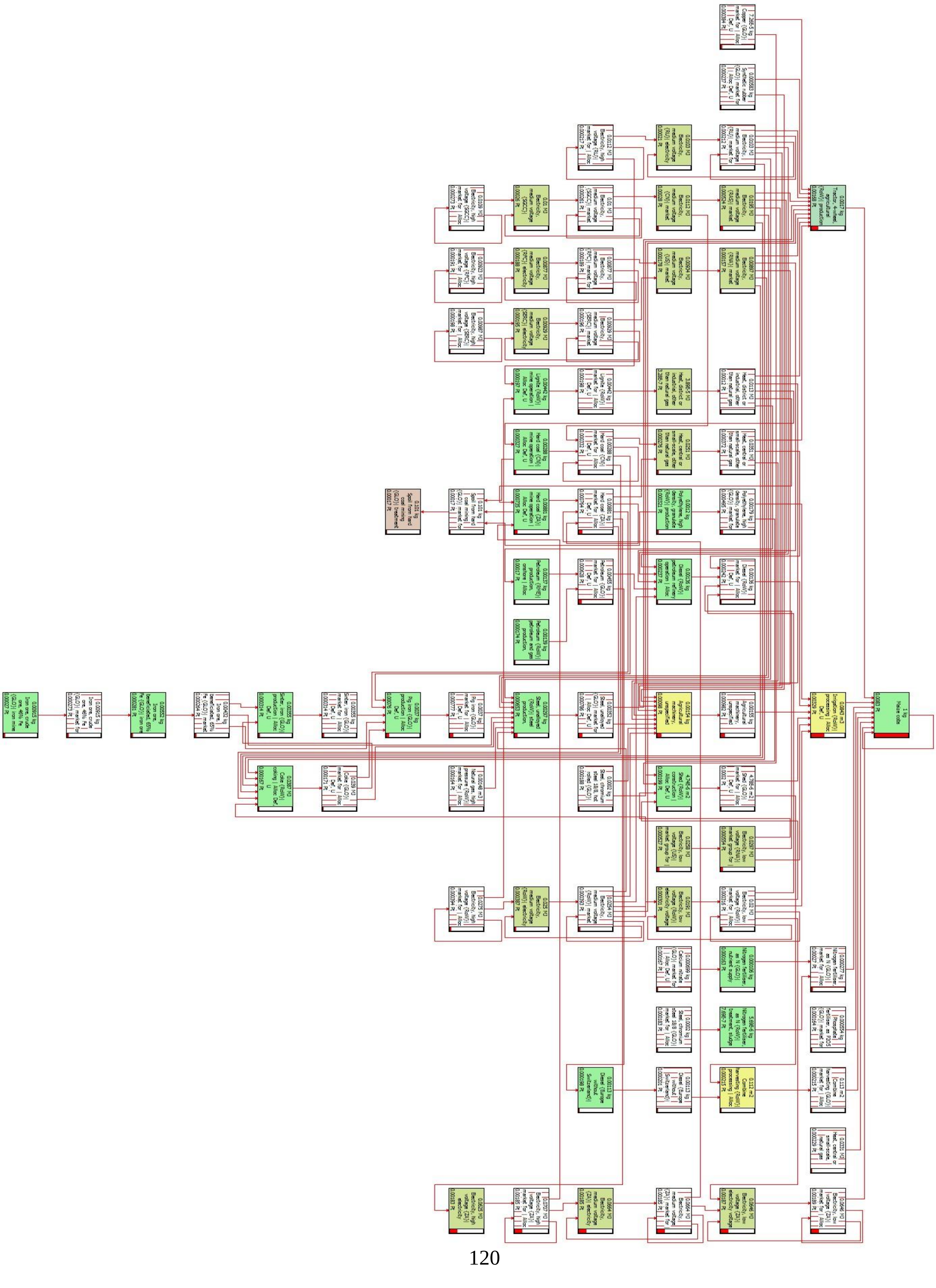
Performance Curves

NK
Standard Pump



GRUNDFOS

Appendix 4: Maize cobs system life cycle network



Appendix 5: Environmental impacts of unit processes

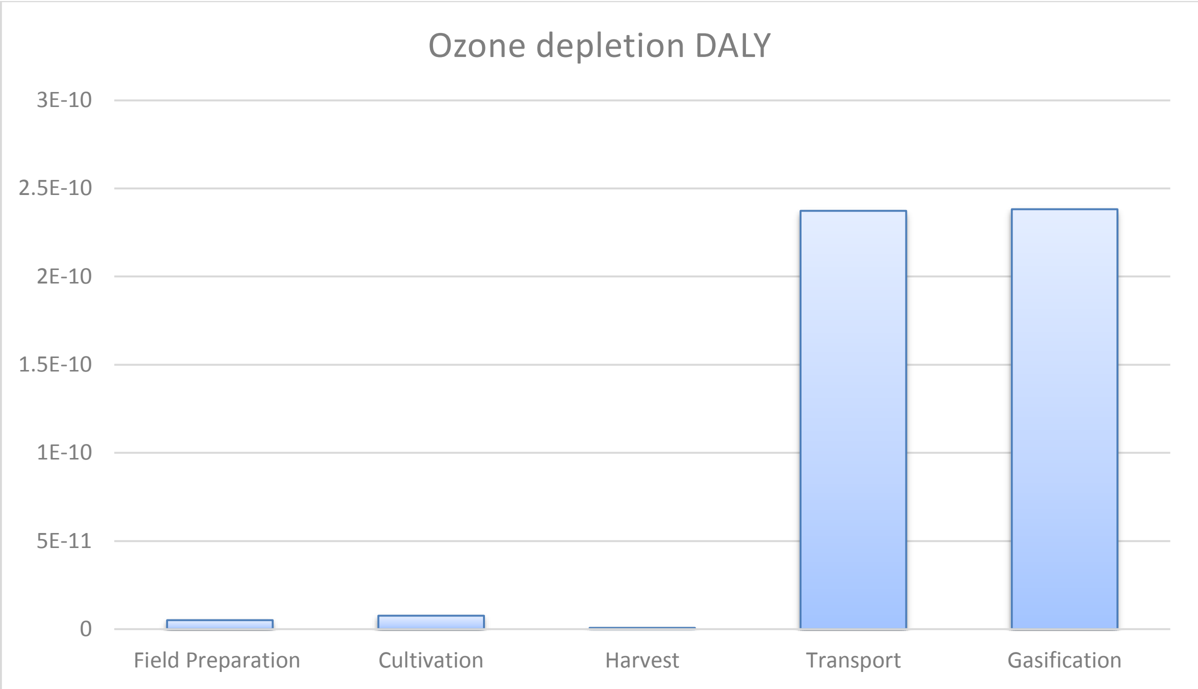


Figure 5.1 Contributions of unit processes to Ozone Depletion

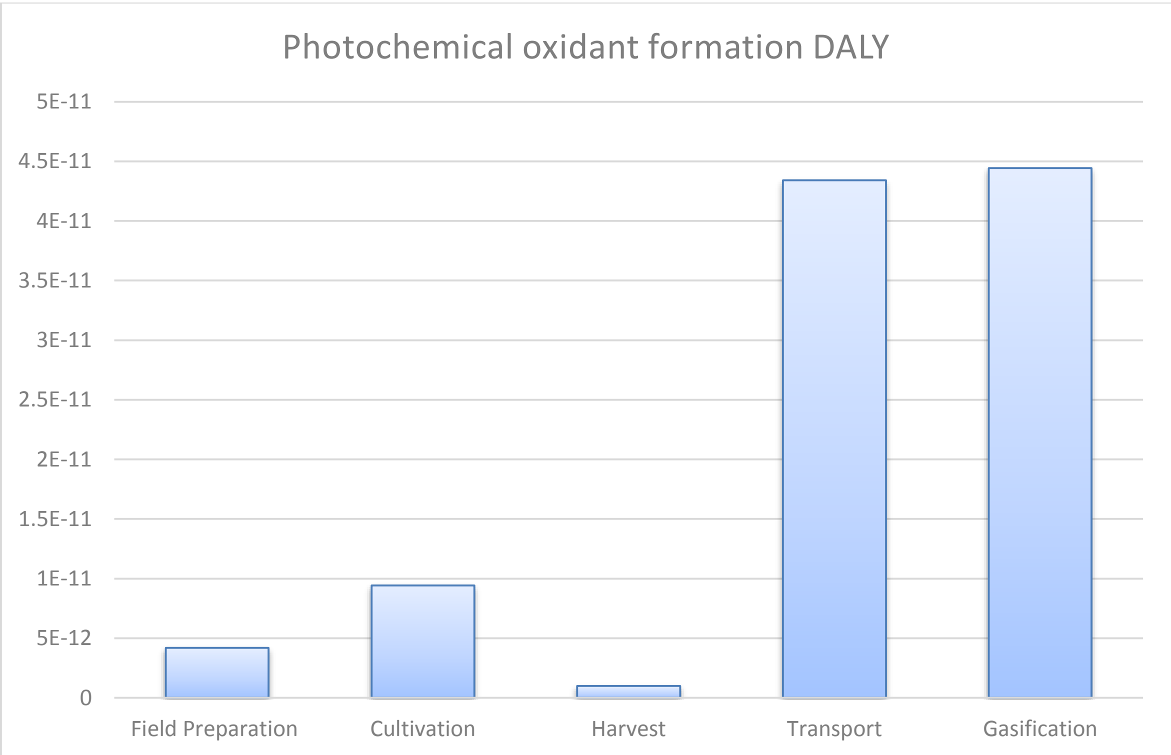


Figure 5.2 Contributions of unit processes to Photochemical Oxidant Formation

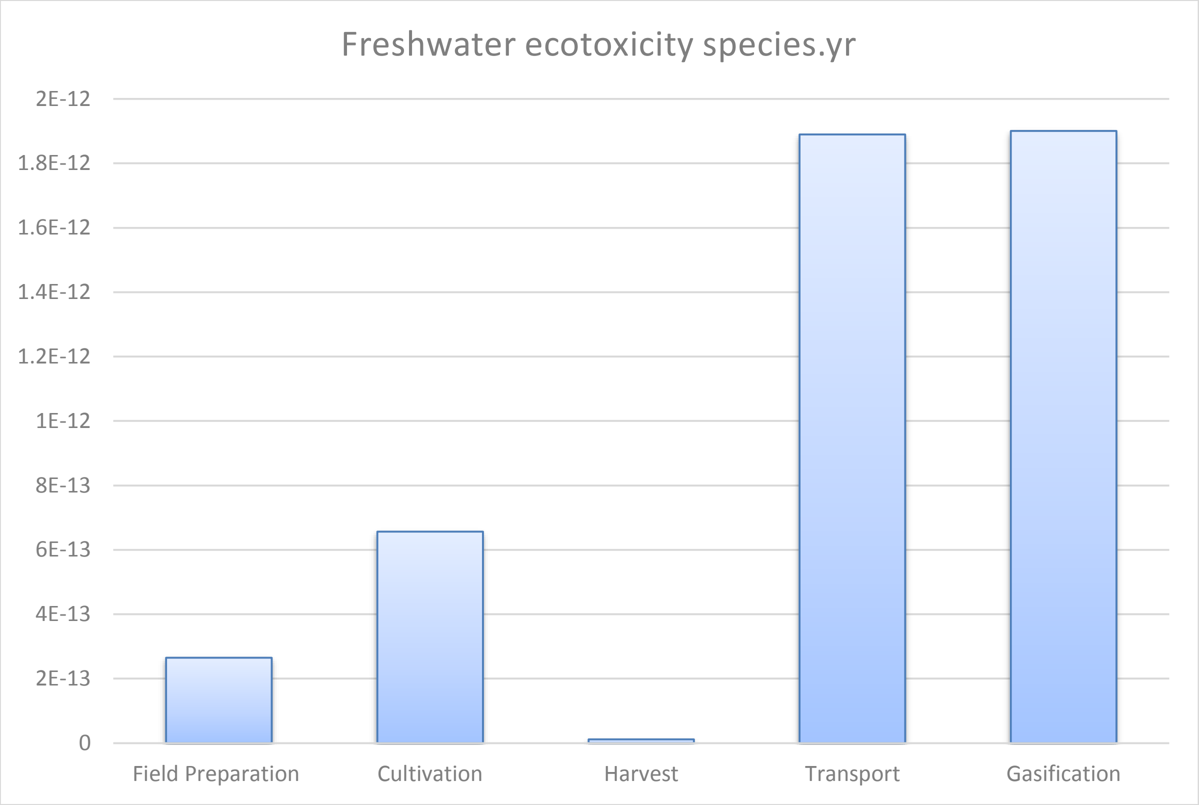


Figure 5.3 Contributions of unit processes to Freshwater Ecotoxicity Species

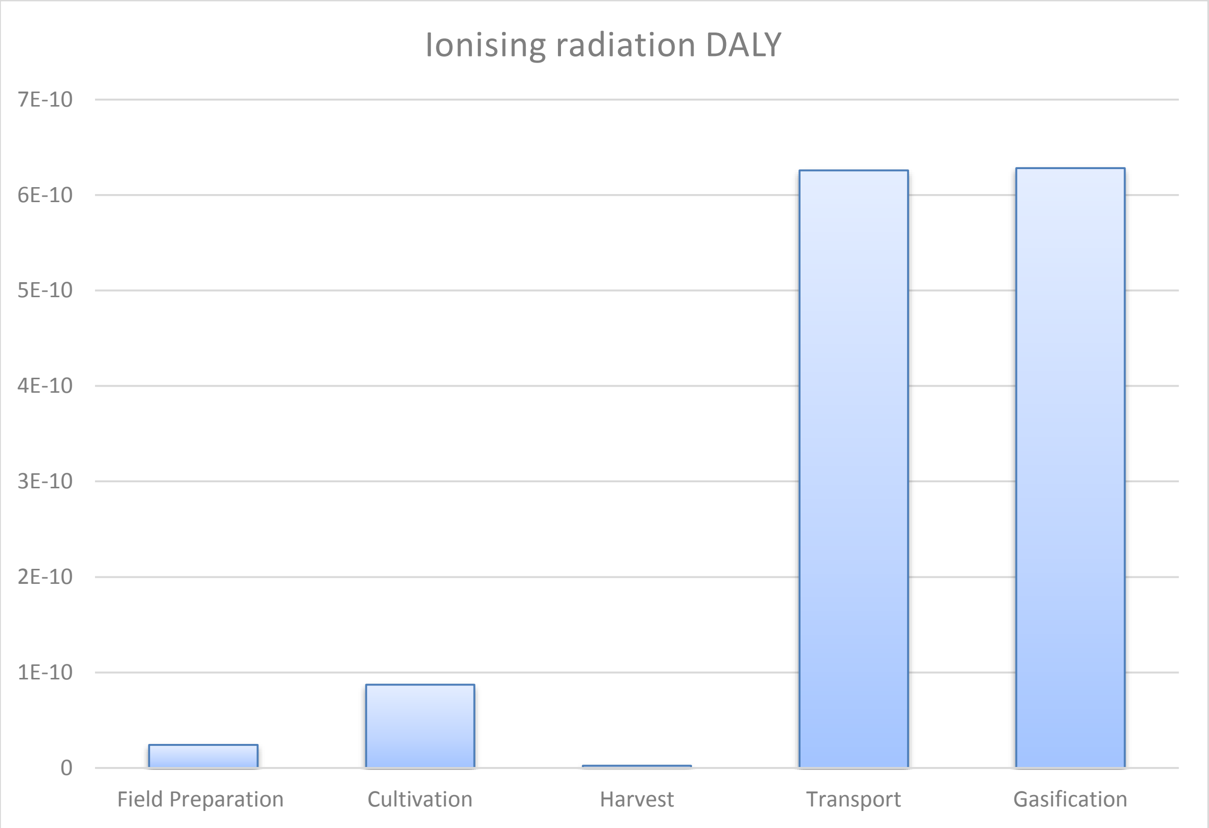


Figure 5.4 Contributions of unit processes to Ionising Radiation

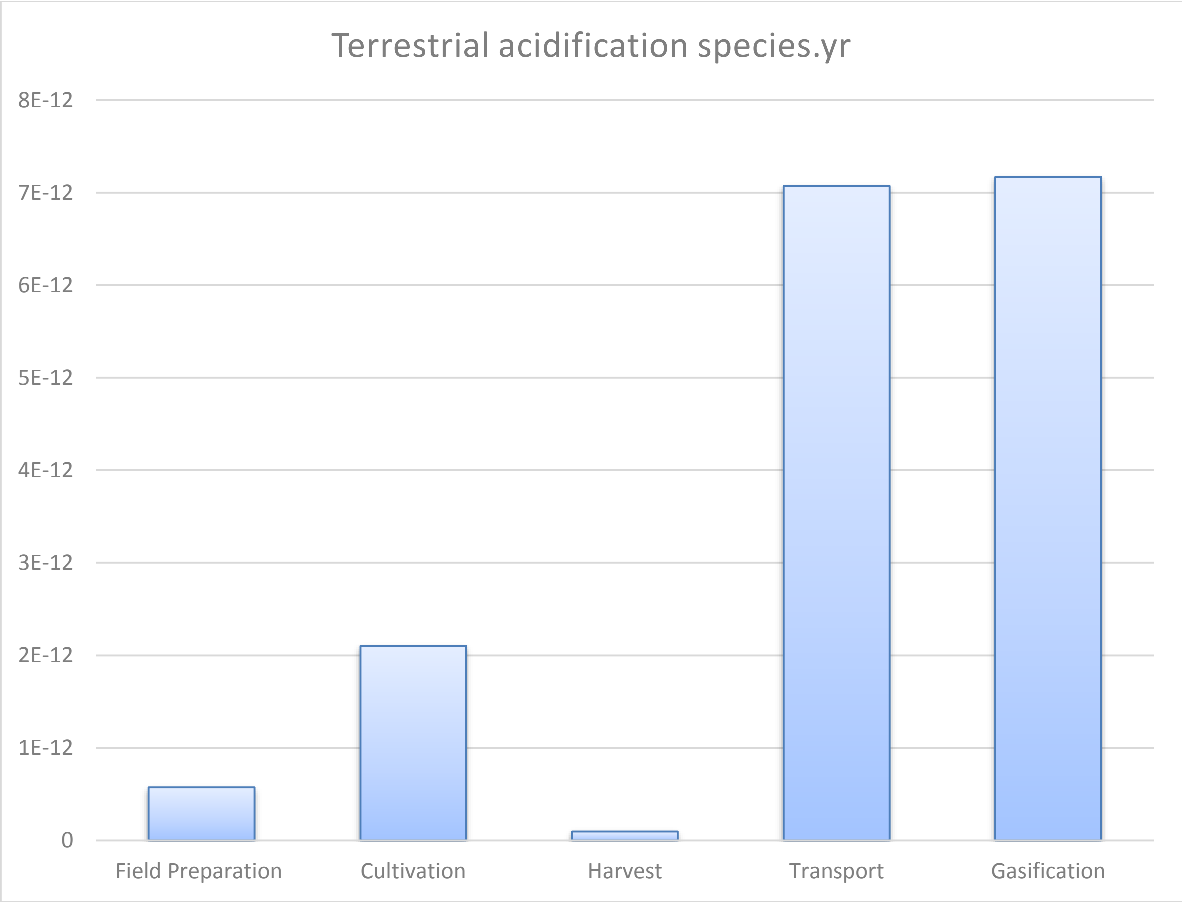


Figure 5.5 Contributions of unit processes to Terrestrial Acidification

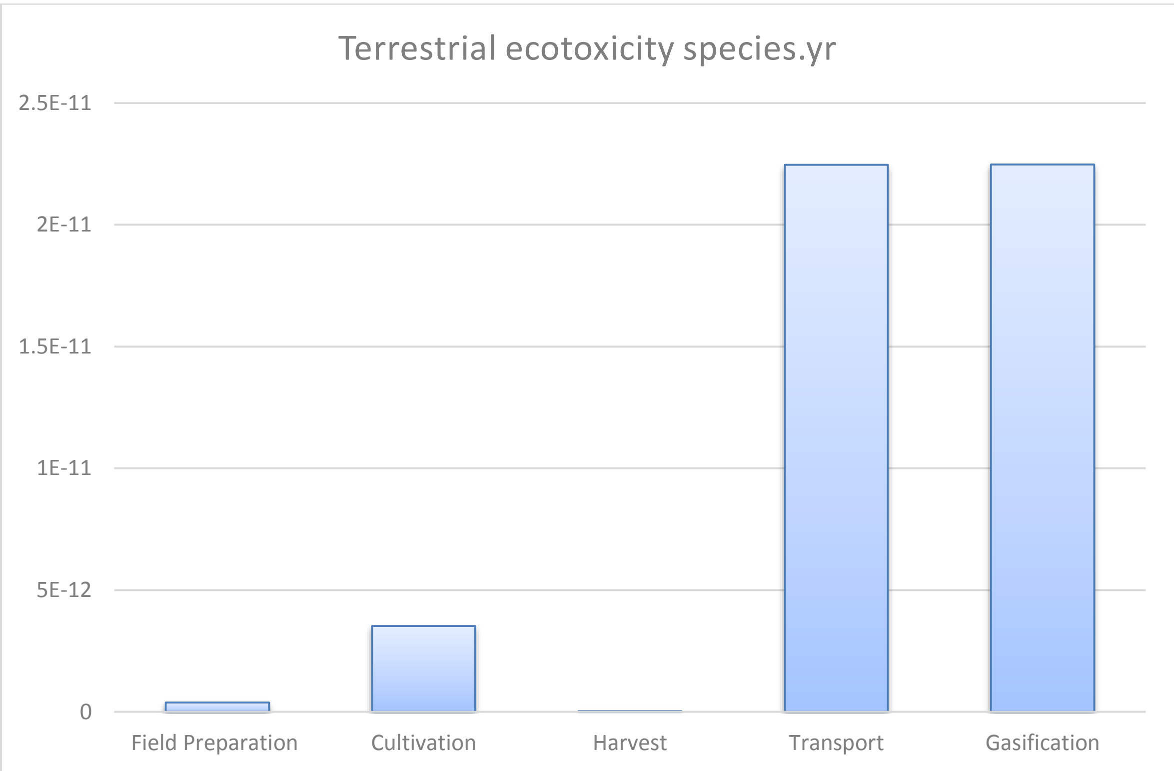


Figure 5.6 Contributions of unit processes to Terrestrial Ecotoxicity

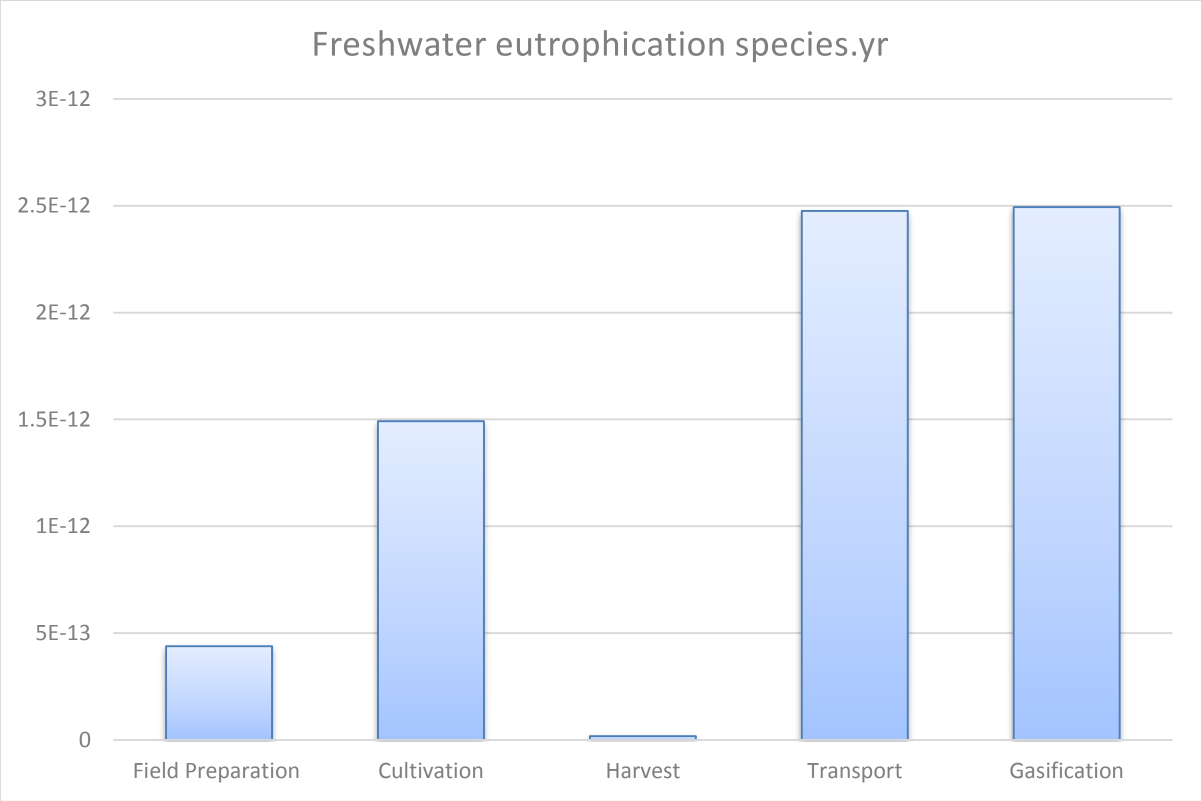


Figure 5.7 Contributions of unit processes to Freshwater Eutrophication

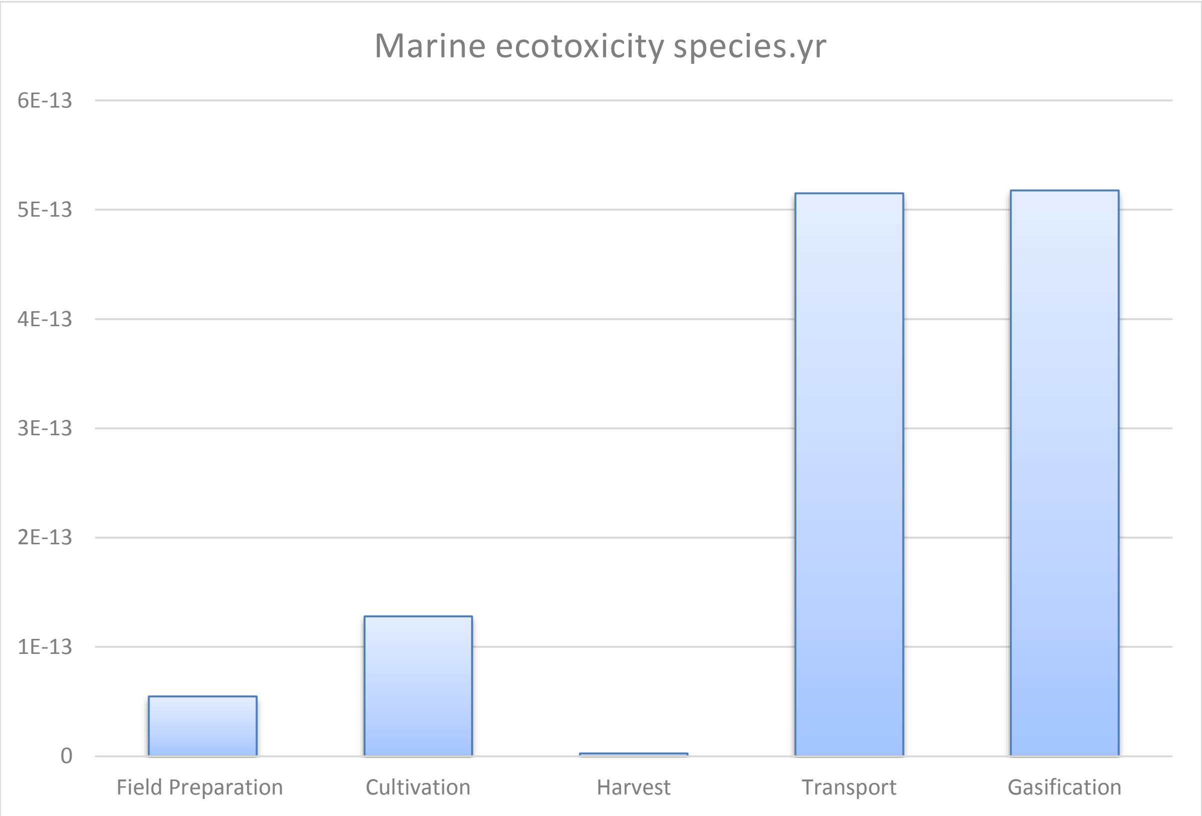


Figure 5.8 Contributions of unit processes to Marine Ecotoxicity

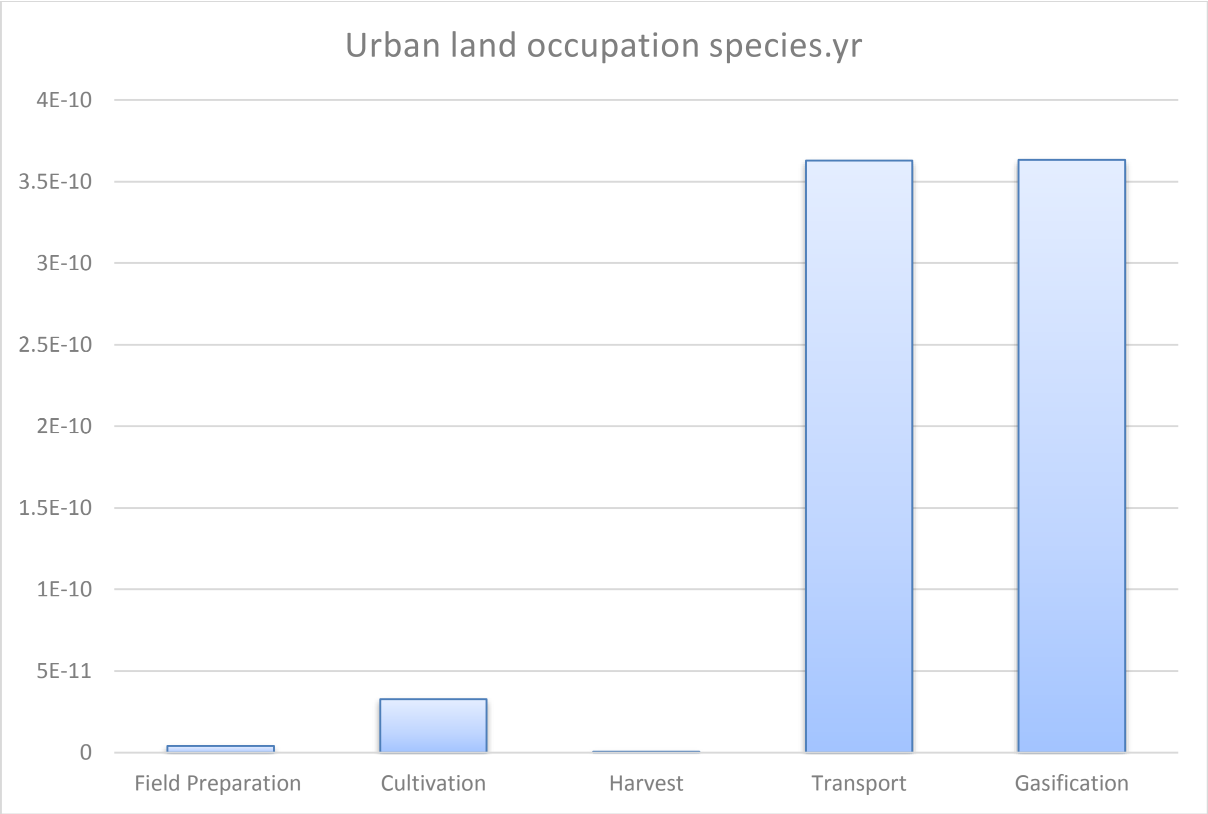


Figure 5.9 Contributions of unit processes to Urban Land Occupation

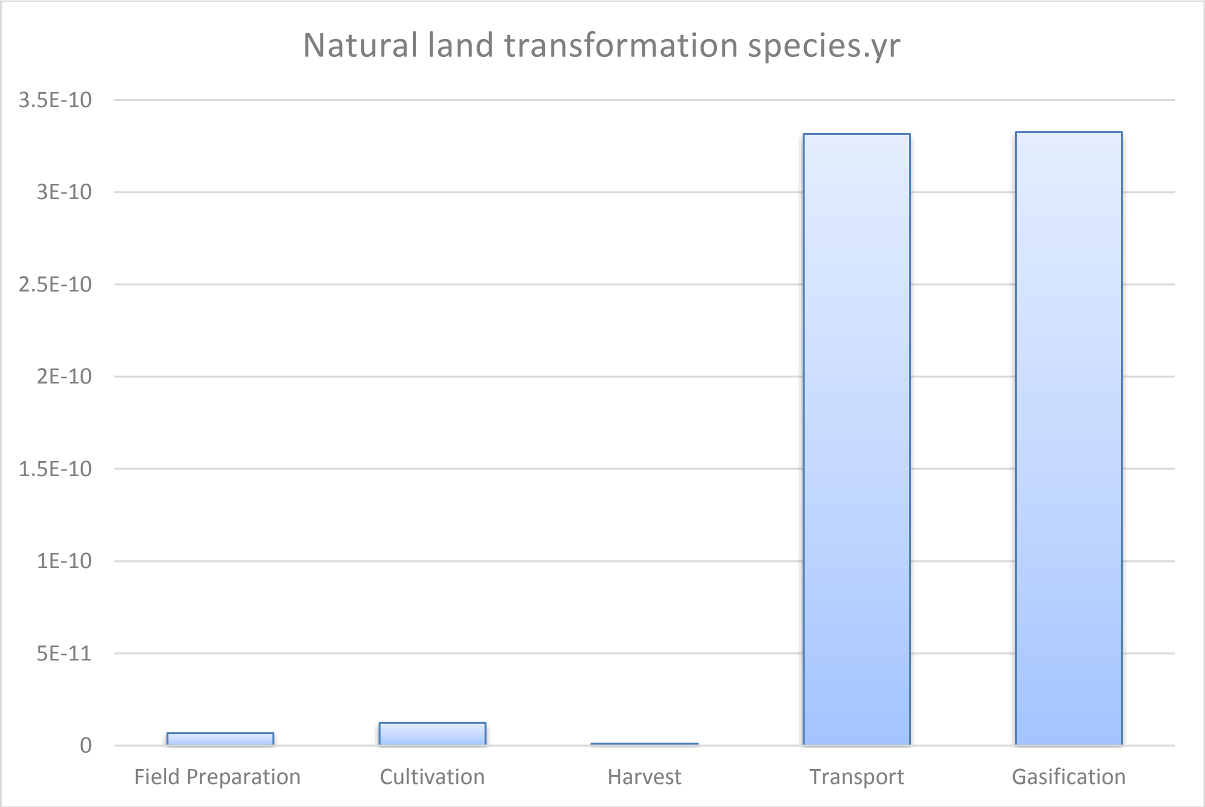


Figure 5.10 Contributions of unit processes to Natural Land Transformation

Appendix 6: Major contributors per impact category for the "maize cobs" system

No	Process	Contribution
FOSSIL DEPLETION		
	Total of all processes	3.57×10^{-3}
	Remaining processes	1.10×10^{-3}
1	Hard coal {ZA}| mine operation	7.74×10^{-4}
2	Polyethylene, high density, granulate {RoW}| production	2.94×10^{-4}
3	Hard coal {CN}| mine operation	2.49×10^{-4}
4	Petroleum {RoW}| petroleum and gas production, on-shore	2.27×10^{-4}
5	Petroleum {RME}| production, onshore	2.24×10^{-4}
6	Lignite {RoW}| mine operation	1.57×10^{-4}
7	Hard coal {RNA}| mine operation	1.48×10^{-4}
8	Polyethylene, high density, granulate {RER}| production	1.45×10^{-4}
9	Hard coal {RoW}| mine operation	1.41×10^{-4}
10	Natural gas, high pressure {RU}| natural gas production	1.08×10^{-4}
METAL DEPLETION		
	Total of all processes	6.61×10^{-4}
	Remaining processes	9.81×10^{-5}
1	Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe	2.83×10^{-4}
2	Chromite ore concentrate {GLO}| production	9.52×10^{-5}
3	Ferronickel, 25% Ni {GLO}| production	4.33×10^{-5}
4	Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining	3.51×10^{-5}
5	Manganese concentrate {GLO}| production	3.20×10^{-5}
6	Copper concentrate {RAS}| copper mine operation	2.81×10^{-5}
7	Copper concentrate {RoW}| copper mine operation	2.40×10^{-5}
8	Copper concentrate {RLA}| copper mine operation	2.18×10^{-5}
NATURAL LAND TRANSFORMATION		
	Total of all processes	1.93×10^{-11}
	Remaining processes	5.83×10^{-12}
1	Onshore well, oil/gas {GLO}| production	9.62×10^{-11}

No	Process	Contribution
2	Land tenure, arable land, measured as carbon net primary productivity, annual crop {BR}| clear-cutting, primary forest to arable land, annual crop	1.35×10^{-12}
3	Pipeline, natural gas, high pressure distribution network {RoW}| construction	9.86×10^{-13}
4	Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}| softwood forestry, mixed species, boreal forest	8.44×10^{-13}
5	Onshore petroleum field infrastructure {GLO}| construction	6.80×10^{-13}
	URBAN LAND OCCUPATION	
	Total of all processes	3.46×10^{-11}
	Remaining processes	1.08×10^{-11}
1	Shed {RoW}| construction	1.10×10^{-11}
2	Irrigation {RoW}| processing	9.06×10^{-12}
3	Drying of bread grain, seed and legumes {RoW}| processing	2.54×10^{-12}
4	Hard coal {CN}| mine operation	1.12×10^{-12}
	AGRICULTURAL LAND OCCUPATION	
	Total of all processes	8.73×10^{-11}
	Remaining processes	2.25×10^{-11}
1	Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management	1.76×10^{-11}
2	Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, spruce, sustainable forest management	1.70×10^{-11}
3	Maize seed, at farm {GLO}| production	8.64×10^{-12}
4	Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}| softwood forestry, mixed species, boreal forest	7.37×10^{-12}
5	Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management	4.24×10^{-12}
6	Sawlog and veneer log, hardwood, measured as solid wood under bark {DE}| hardwood forestry, beech, sustainable forest management	3.67×10^{-12}
7	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, pine, sustainable forest management	3.21×10^{-12}
8	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, spruce, sustainable forest management	3.11×10^{-12}

No	Process	Contribution
MARINE ECOTOXICITY		
	Total of all processes	1.71×10^{-13}
	Remaining processes	2.70×10^{-14}
1	Spoil from hard coal mining {GLO}| treatment of, in surface landfill	4.71×10^{-14}
2	Sulfidic tailing, off-site {GLO}| treatment of	3.34×10^{-14}
3	Spoil from lignite mining {GLO}| treatment of, in surface landfill	2.89×10^{-14}
4	Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration	1.80×10^{-14}
5	Nickel smelter slag {RoW}| treatment of, residual material landfill	1.63×10^{-14}
FRESHWATER ECOTOXICITY		
	Total of all processes	8.64×10^{-13}
	Remaining processes	1.08×10^{-13}
1	Spoil from hard coal mining {GLO}| treatment of, in surface landfill	2.41×10^{-13}
2	Sulfidic tailing, off-site {GLO}| treatment of	1.82×10^{-13}
3	Spoil from lignite mining {GLO}| treatment of, in surface landfill	1.48×10^{-13}
4	Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration	1.02×10^{-13}
5	Nickel smelter slag {RoW}| treatment of, residual material landfill	8.21×10^{-14}
TERRESTRIAL ECOTOXICITY		
	Total of all processes	3.68×10^{-12}
	Remaining processes	1.17×10^{-12}
1	Phosphate fertiliser, as P2O5 {GLO}| nutrient supply from coconut husk	9.74×10^{-13}
2	Maize seed, at farm {GLO}| production	4.22×10^{-13}
3	Nitrogen fertiliser, as N {GLO}| nutrient supply from coconut husk	3.27×10^{-13}
4	Soybean {AR}| soybean production	3.08×10^{-13}
5	Compost {CH}| treatment of biowaste, composting	2.00×10^{-13}
6	Carrot {RoW}| carrot production	1.53×10^{-13}
7	Carrot {CN}| carrot production	1.32×10^{-13}
FRESHWATER EUTROPHICATION		
	Total of all processes	1.80×10^{-12}
	Remaining processes	8.07×10^{-14}

No	Process	Contribution
1	Spoil from hard coal mining {GLO}| treatment of, in surface landfill	8.84×10^{-13}
2	Spoil from lignite mining {GLO}| treatment of, in surface landfill	5.54×10^{-13}
3	Sulfidic tailing, off-site {GLO}| treatment of	2.85×10^{-13}
	TERRESTRIAL ACIDIFICATION	
	Total of all processes	2.64×10^{-12}
	Remaining processes	1.63×10^{-12}
1	Electricity, high voltage {ZA}| electricity production, hard coal	9.37×10^{-13}
2	Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	7.35×10^{-14}
	CLIMATE CHANGE ECOSYSTEM	
	Total of all processes	5.79×10^{-10}
	Remaining processes	3.96×10^{-10}
1	Electricity, high voltage {ZA}| electricity production, hard coal	1.40×10^{-10}
2	Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	2.26×10^{-11}
3	Pig iron {GLO}| production	2.10×10^{-11}
	CLIMATE CHANGE HUMAN HEALTH	
	Total of all processes	1.02×10^{-7}
	Remaining processes	6.99×10^{-8}
1	Electricity, high voltage {ZA}| electricity production, hard coal	2.46×10^{-8}
2	Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	3.99×10^{-9}
3	Pig iron {GLO}| production	3.71×10^{-9}
	IONISING RADIATION	
	Total of all processes	1.07×10^{-10}
	Remaining processes	1.84×10^{-11}
1	Tailing, from uranium milling {GLO}| treatment of	5.73×10^{-11}
2	Low level radioactive waste {CH}| treatment of, plasma torch incineration	1.89×10^{-11}
3	Spent nuclear fuel {RoW}| treatment of, reprocessing	1.20×10^{-11}
	PARTICULATE MATTER FORMATION	
	Total of all processes	5.20×10^{-8}

No	Process	Contribution
	Remaining processes	3.25×10^{-8}
1	Electricity, high voltage {ZA}| electricity production, hard coal	1.07×10^{-8}
2	Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe	3.21×10^{-9}
3	Electricity, high voltage {IN}| electricity production, lignite	2.17×10^{-9}
4	Electricity, high voltage {RFC}| electricity production, lignite	1.82×10^{-9}
5	Electricity, high voltage {SERC}| electricity production, lignite	1.58×10^{-9}
	PHOTOCHEMICAL OXIDANT FORMATION	
	Total of all processes	1.37×10^{-11}
	Remaining processes	7.14×10^{-12}
1	Electricity, high voltage {ZA}| electricity production, hard coal	3.01×10^{-12}
2	Combine harvesting {RoW}| processing	7.64×10^{-13}
3	Tractor, 4-wheel, agricultural {RoW}| production	7.12×10^{-13}
4	Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW	6.05×10^{-13}
5	Irrigation {RoW}| processing	5.41×10^{-13}
6	Tillage, ploughing {RoW}| processing	4.48×10^{-13}
7	Agricultural machinery, unspecified {RoW}| production	4.32×10^{-13}
	HUMAN TOXICITY	
	Total of all processes	2.63×10^{-8}
	Remaining processes	5.88×10^{-9}
1	Spoil from hard coal mining {GLO}| treatment of, in surface landfill	7.98×10^{-9}
2	Sulfidic tailing, off-site {GLO}| treatment of	7.55×10^{-9}
3	Spoil from lignite mining {GLO}| treatment of, in surface landfill	4.89×10^{-9}
	OZONE DEPLETION	
	Total of all processes	2.54×10^{-11}
	Remaining processes	6.07×10^{-12}
1	Trichloromethane {RER}| production	7.65×10^{-12}
2	Trichloromethane {RoW}| production	4.17×10^{-12}
3	Petroleum {RoW}| petroleum and gas production, on-shore	2.43×10^{-12}
4	Petroleum {RME}| production, onshore	2.40×10^{-12}

No	Process	Contribution
5	Petroleum {RU}| production, onshore	1.03×10^{-12}
6	Transport, pipeline, long distance, natural gas {RU}| processing	8.40×10^{-13}
7	Natural gas, high pressure {US}| petroleum and gas production, on-shore	8.13×10^{-13}