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Life cycle assessment of jatropha oil as a biofuel for transports in rural Mozambique

Master of Science Thesis

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Abstract

The world is facing a big challenge to prevent further environmental damage. Fossil energy reserves are running out and the global warming is a fact. The transportation sector is one of the most fossil energy consuming sectors and the combustion of fossil fuels contributes to increased greenhouse gas concentrations in the atmosphere. The use of biofuels could decrease the dependency of fossil fuels and help stabilizing the greenhouse gas levels in the atmosphere.

Chikweti Forests of Niassa, a forest company in northern Mozambique, is installing a biodiesel plant to produce fuels and thereby reduce dependency on imported diesel in this remote location. The biodiesel will be produced of oil pressed from the seeds of the jatropha plant. It was concluded at an early stage of this study that it was more feasible to blend jatropha pure plant oil into fossil diesel than to produce biodiesel, as the last production step is resource demanding. Hence, jatropha oil rather than biodiesel was considered.

This master thesis was a case study including a field study to the jatropha plantations and the production plant outside Lichinga, Mozambique. The aim was to examine the environmental impacts of producing jatropha oil using the method of life cycle assessment. The impact categories chosen where fossil energy use, global warming potential and water use. The work included a literature study in order to review different methods for including water use in life cycle assessment and to find missing pieces of data. Since water use assessment is a relatively new field, the thesis studied some water use indicators in literature and developed a new indicator handling water use in life cycle assessment. The water use indicators assessed in this study where the water footprint and local hydrological cycle deviations, the indicator developed exclusively by the authors of this master thesis. The results where compared with the reference system, which was imported fossil diesel.

The results showed that using jatropha pure plant oil would reduce the fossil energy use to one third and the global warming potential would reduce to one half compared to the reference system. Comparing the water use, using the two different indicators, for the jatropha production system and the reference system showed that the water footprint was 10 000 times larger for the jatropha system due to the accounting of rain water. When using the indicator local hydrological cycle deviation, the results showed a reduction of the water use with almost one third when choosing the jatropha production system. This due to the fact that the local hydrological cycle devition only accounts water that is removed from the local hydrological cycle.

The report also contains suggestions on future developments of the jatropha production system in Lichinga and an extensive discussion on the methodology of life cycle impact assessment, mostly regarding water use.

Keywords

Life cycle assessment, jatropha, biodiesel, local hydrological cycle deviation, water footprint, Mozambique.

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1 Introduction

In chapter one, the master thesis is introduced with background information about jatropha, jatropha fuel and land use rights in Mozambique. Some information about the forest company Chikweti and the principle of carbon credits will be described. In the end of this chapter, the aim, the method and the process of data acquisition will be presented.

A significant amount of the environmental problems of today are largely or partly caused by the use of fossil fuels. Most notably is climate change, the warming of the atmosphere which is much due to the release of fossil carbon dioxide (CO_2) to which transportations is a major contributor (IPCC, 2007). Efficient modes of transportation are also a fundamental part of socio-economic development in developing countries, connecting and expanding markets. The cultivation of biofuels also creates rural jobs and has the potential to deliver the fuel even where infrastructure is lacking (Francis et al., 2005).

There exist a number of fuels based on renewable sources rather than fossil fuels. However, through life cycle assessment (LCA) studies, it has been shown that these may sometimes contribute more to environmental problems than the fossil alternative. See for instance Farell et al. (2006) who reviewed the global warming potential of bioethanol from different sources. Since it is not certain that the total environmental impacts of renewable sources are less than those of the fossil alternatives, it is important to assess these new, renewable fuels with regard to their environmental impacts.

One such alternative fuel is oil from the bush jatropha. The oil can be used pure in some engines, as a blend with diesel or converted through the process of transesterification into biodiesel, also known as jatropha methyl esther (JME) (Gübitz et al., 1999). Jatropha as a feedstock is to this date not thoroughly examined, as a contrast to other feedstocks such as oil palm or rapeseed (see e.g. Arvidsson et al., 2010)

1.1 Jatropha

The *jatropha curcas linnaeus* plant is a large bush or a small tree that can reach a height of approximately 5m and reach an age of about 50 years (Achten et al., 2008, Heller, 1996). An ambitious description of jatropha and its uses has been conducted by Heller (1996) which describes the jatropha tree as havings 5-7 shallow lobed leaves with a length and width of 6-15 cm which are alternate arranged on the branches, see figure 1.1. After pollination a tricolor ellipsoidal fruit is formed which matures after 90 days. The fruit contains two or three seedswhich are black with a length and thickness of 2 cm and 1 cm respectively, see figure 1.2.

Figure 1.1. Jatropha plant with mature fruits.

Figure 1.2.A cracked open mature fruit, containing two seeds. The seeds are easy to separate from the hull.

All parts of the plant, after preparation, can be used as medicine for humans and animals. The branches contain latex,which has antimicrobial propertiesagainst some bacteria.The oil can be used to ease the pain caused by rheumatism and has strong cleansingproperties to promote skin diseases. The plant has also insecticidal properties andthe oil can be used as a pesticide to control some pests attacking cotton, potato, pulse, mungbean, corn and sorghum.

The fruits and the seeds are harvested several months after the rainy season andthe seeds can be pressed to extract the oil. The yield is highly dependent on location, weather conditions, genetics, plant age and management (Achten et al., 2008). As further stated by Heller (1996), the oil can be used in soap production, for medical purposes, as vegetable oil that could be used as a fuel, or to be further processed into methyl esters which is used as biodiesel. The extracted oilmainly consist of palmitic (C16:0), stearic (C18:0), oleic (C18:1) and linoleic acid (C18:2), which are fatty acids. The seeds are toxic due to the content of the toxic protein curcin and diterpene esters. Curcin hinders protein synthesis in vitro and the diterpene esters can promote skin tumors.

The remaining seed cake after pressing the oil can be used as animal fodder if it is first detoxified. It can also be used as a fertilizer because of its high nutrient content. As a fertilizer it is very similar in nutrient content as the seedcake of castor bean or the manure from chicken with a nitrogen content ranging from 1.5to 4 percent. Fruit hulls and seed shells can be combusted or used as a fertilizerif returned to the fields.

The jatropha plant is best adapted to arid and semi-arid conditions such as grassland-savanna, thorn forest scrub and caatingas vegetation. The soil should be well drained with a good aeration. It is not, however, highly dependent on nutrient content and can be grown on marginal soils. Studies show that jatropha is best adapted to dryer regions of thetropics but the yield is highly dependent on rainfall. The optimal annual rainfall is between 300-1000 mm and the temperature should be between 20-28°C. Jatropha is best adapted at lower altitudes, from sea level to 500m, and is not sensitive to day length.

The plant is commonly used as a living fence at fields and settlements because it can easily be propagated by cuttings and it is not browsed by cattle. Because of this easy propagation it serves as erosion control, further protecting the fields which it surrounds.

The origin of the plant is not fully established but according to Heller (1996), Mexico and Central America are likely the places of origin. Today jatropha is also cultivated in Latin America, Asia and

Africa. Heller (1996) also discusses the possibility that it was Portuguese seafarers that brought the jatropha plant to countries in Africa and Asia. According to literature, jatropha is a promising plant with many good properties that can be used to produce renewable fuel for transportation in tropical countries (Achten et al., 2010, Heller, 1996, Gübitz et al., 1999).

1.2 Jatropha pure plant oil and jatropha methyl ester

The global challenges of climate change have influenced research of alternative transportation fuels. In this context, biofuels, which are renewable fuels of biological origin, have been outlined as an alternative. The largest environmental advantage of using biofuels is that the carbon dioxide (CO_2)emitted is balanced with the carbon assimilated from the atmosphere during the growth phase of the biomass.

Vegetable oil can be extracted from any oil-containing crop and can be used directly as a biofuel in some engines (Heller, 1996). The oil mostly consists of triglycerides, molecules with three fatty acids coupled to glycerol (Agarwal and Kumar Agarwal, 2007).When the diesel engine was developed, the inventor Rudolf Diesel stated as early as 1911 that his engine could be run on pure plant oil and could potentially replace fossil fuel in the transportation sector.

Pure plant oil (PPO) can be transesterified into methyl esters where methanol replaces the glycerol in the triglyceride, forming glycerol as a by-product. The formed methyl ester, the biodiesel, can be used as a fuel and is suitable for direct use in any diesel engine.

Jatropha is a crop which is promising when it comes to the production of biofuels. The pressed jatropha PPO can be used directly in some diesel engines, e.g. Deutz. Hatz, IFA, Elsbett, DMS, Farymann and Lister-type (Heller, 1996).Blending the PPO into diesel has been tested and studied at different blending ratios in several studies with promising results (Forson et al., 2004, Agarwal and Kumar Agarwal, 2007, Pramanik, 2002). In addition, a popular purpose of jatropha cultivation is to produce biodiesel by the process of transeterification. In this process, the jatropha PPO is converted into jatropha methyl ester (JME), which can be combusted in any diesel engine, with good performance (Heller, 1996, Gübitz, 1999).

1.3 Mozambique

Mozambique hasa population of about 20 million,is located on the east coast of Africa, and is among the poorest countries in the world (CIA, 2011). The total area is approximately 785 000 km^2 and the neighboring countries are Tanzania, Malawi, South Africa, Zambia and Swaziland. Mozambique is divided into ten provinces: Cabo Delgado, Niassa,Nampula, Zambézia, Tete, Manica, Sofala, Inhambane, Gaza, and Maputo. The independent republic of Mozambique was formed in 1975 with Samora Machel as the first president. In the first election 1994, the party Frelimo won against the other participating party Renamo. A third of the population nourish on farming, mostly food crops like maize but also sorghum and cassava. Some cash crops are also cultivated. These are most commonly sugar, cashew nuts, cotton, tea and tobacco (Schut et al., 2010, Arndt et al., 2010). However, the production is normally low without modern cultivation methods and irrigation (Hanlon, 2011a). The annual rainfall of Mozambique varies greatly between different regions.In the northern and central parts of the country, there are semi-arid, wet and sub-humid. The rest of the country consists mainly of low-lying coastal and semiarid plains making northern parts more reliable for farming due to more rain (Schut et al., 2010).

The energy use in Mozambique has increased since the 1980s and the fuel prices are high. Mozambique is dependent on imports of fossil fuel since they lack domestic production. Electricity used is often imported from South Africa but they do produce hydropower electricity by the Cahora Bassa dam which they export (Schut et al., 2010, Ribeiro and Matavel, 2009).

Mozambique is considered as having the largest potential for biofuel production in Africa and the government sees great opportunities in biofuel production such as socio-economic development in rural areas and reducing the dependency of imports of fossil energy. The potential is estimated to a production of 7 EJ bioenergy while the domestic consumption is expected to be much lower, leaving room for export. It is also easy to produce bioenergy in Mozambique due to less stricter regulations (Nhantumbo et al., 2010). Present projects are thus developed in areas with good services. This new industry can also create many job opportunities (Nielsen et al., 2011). The hope is that biofuels can cover 15 percent of their fuel consumption within five years (Schut et al., 2010)

The country has about 36 million hectares of arable land but at present only about 10 percent is cultivated (Schut et al., 2010). According to a study made in 2008/2009, about 54 percent of the area is suitable for agriculture including biofuel production, and the rest is more suitable for forestry and grazing (Nielsen et al., 2011). The good climate and soils makes Mozambique very suitable for jatropha production and the plant has been used here before for many years as a medical plant (Nielsen et al., 2011). Mozambique has recently received many requests from different organizations who want to use land to produce biofuels, land requests of about 20 million hectares in total. This number includes requests for production of jatropha biofuel (Arndt et al., 2010). The most advanced jatropha producer in Mozambique is the Sun biofuels in Manica and today, about 16 different jatropha projects are under development in Mozambique (Hanlon, 2011a). Other jatropha projects in Mozambique are ESV Bio Africa, Energem Renewable, Energy LDA , Enerterra, Deulco Energias Renovaveis, MoçamGalp and AVIAM (Ribeiro and Matavel, 2009).

All land in Mozambique belongs to the state and cannot be sold. When wanting to lease land a DUAT (Direito de Uso a Aprovietamento dos Terras) can be applied which is a lease contract valid for a period of 50 years. After the time expired, the DUAT can be renewed. There are three different types of land ‘ownership’ in Mozambique:

1. The land is already occupied by a community (group of people living in the same area) using the land to make a living. The users then have the right to use the land.
2. The land is used by occupants that have been using it for at least ten years in good faith and thus have the right to do so.
3. The land is used by a person/organization/company that has sent a formal request to the state, including a community consultation, and has got an approval to use the land (Schut et al., 2010, Hanlon, 2011a).

The time limit of 50 years does not apply for group 1 and 2 which have permanent rights and not have to receive a document of the DUAT if not the land is to be used for a commercial purpose (Hanlon, 2011a). A DUAT can be transferred from one person to another without having to notify the state. For foreigners wanting to invest in land, different rules apply. The investment project first needs to be approved before a DUAT can be applied and has to be signed by the Ministry for Planning and Development (Schut et al., 2010).

The best area for jatropha production is in the northern parts due to good climate conditions and more need of new jobs. Due to transportation problems however, most investors stake on production in southern parts (Hanlon, 2011b). Mozambique has three large harbor ports and they are located in Beira, Nacala and Maputo but unfortunately the roads heading inlands are in bad condition. In southern Africa, Mozambique has the lowest road density which makes transportation difficult (Schut et al., 2010). Another problem in Mozambique is water scarcity and the lack of measures in water conservation. Since the production of biofuels is water demanding, problems can occur when competing with food production and making people move to other places in search for water which puts even more pressure on the water resources (Nielsen et al., 2011). The water use rights associated with the production of jatropha biofuel has not yet been discussed but is important to consider in the future since it requires a lot of water (Hanlon, 2011b).

1.4 Chikweti

The company Chikweti Forests of Niassa is an expansive forest company, founded in 2005 in Lichinga, Mozambique. The main objective of the company is to turn low productive land into highly productive plantations with forest stewardship council (FSC) environmental certification.The goal is to plant 60 000 ha of mostly pine, but also some eucalyptus trees. Because diesel is a high cost and the supply is erratic, Chikweti also aims to be self-sufficient on biofuels from jatropha, through its subsidiary Luambala Jatropha Ltd.

Chikweti´s total area of operations is about 140 000 ha, and there is hence a need for fast transportations around the area. The jatropha oil is intended to provide fuel for these transports but in the long term also for forestry machines (Chikweti, 2010). They are applying for a jatropha plantation of 10 000 ha in Luambala, outside of Lichinga, but currently less than 300 ha has been planted. The immediate objective is to produce PPO but in the future JME may be produced to substitute fossil diesel to a large extent.

1.5 Carbon credits

Trough photosynthesis,plantsassimilate and store CO_2 as biomass. This is an important function especially in these times with society disturbing the carbon balance by emitting more CO_2 from fossil sources. Forests can serve as carbon pools and affect the greenhouse gas balance in a positive way. When planting new forests, it allows more uptake of CO_2 from the atmosphere. Planting of trees causes a positive effect while deforestation causes an immediate negative effect. It is important to consider what kind of land the trees are planted on. If natural forest is cleared to give space to new plantations it can take many years to pay back the loss. Deforestation is estimated to be the source of 20 percent of the total greenhouse gas emissions in the world (Westholm, 2008).

The Kyoto protocol that was agreed on in 1997 defined the Clean Development Mechanism (CDM) which has two goals: to help industrial countries to reach the GHG goal set by the Kyoto protocol and to help developing countries to achieve sustainable development (Bakker, 2006). The CDM is a project-based flexible mechanism which aims to make Annex 1 countries (most industrialized contries) invest in climate projects in developing countries (Westholm, 2008). One part of reaching the goal is to reduce the green house gas emissions by purchasing Certified Emission Reductions (CER) which focus on the GHG emissions (Bakker, 2006). One CER is equal to 1 ton of CO_2-equivalents and is a reduction credit which the industrial countries earn when investing in climate projects in developing countries (Westholm, 2008). Developing countries can earn CERsthat they can sell to industrial countries. With this trade, the industrialized country buys permits to emit GHG which they have paid off somewhere else (Bakker, 2006).

There are two types of markets for carbon trading, the regulated market and the voluntary market. The regulated market is regulated by the Kyoto protocol or other national systems. The voluntary market includes the acts between different actors, procedures and certificates. The two markets can be mixed when selling and buying credits and permits, but voluntary credits are not sold on regulated markets. The selling and buying can be directly between the companies/countries or sold through an intermediary which can be carbon funds, traders or brokers.

In the Kyoto protocol the forestry is included in the category "Land use and land use change forestry". Carbon sequestration is the mechanism where carbon is collected and sequestered in storage. When it comes to forestry, carbon sequestration is when trees are planted and store carbon from the air (Westholm, 2008).

One intermediary carbon fund is "The carbon credit trust". They offer suggestions of projects and assistance during the trade. Projects that can earn carbon credits are waste-to-energy, energy efficiency, waste management and avoiding of landfills, recycling, water and wastewater efficiency, forestry and tree planting, landfill gas electricity generation, renewable energy projects or clean energy projects. An organization interested in this trade, first measures their greenhouse gas emissions, and then designs a strategy to reduce the energy use and emissions. Then they show with management that they are really working actively with carbon reduction. The carbon credit trust will then help the organization with an audit, providing recommendations (Carbon credit trust, 2008).

When it comes to forestry, the CDM has two different activities, afforestation and reforestation (AR). There are two types of CER for AR, the short term CER and the long term. The short term CER needs to be replaced when expired, but the long term does not expire until the project ends or the credit period expires. The short term CER costs 5-20 €/ton CO_2 but the price for CER for biofuels is expected to be much higher (Bakker, 2006).

When calculating the carbon credits earned from carbon sequestration or avoided deforestation, a construction of a baseline scenario is necessary. This scenario can be constructed with historical or existing emission levels, emissions from an alternative attractive technology or by considering similar projects which have similar circumstances and emissions (Westholm, 2008).

1.6 Aim

The aim of this study is to assess the environmental impacts of jatropha oil produced and used as a fuel for transports, using LCA. The jatropha oil is to be used by the forest company Chikweti in Lichinga, Mozambique. The focus is to assess the impact categories global warming potential, fossil energy useand to assess water use. A special focus will be put on water use, considering the risks of water scarcity in Mozambique, which was described above. The LCA is also used as a tool to gain knowledge about the functionality and rationality of the production system.

The study also aims to develop the conditions for large scale jatropha cultivation by examining the potential for acquiring carbon credits for the JME production scheme and the potential to involve local farmers in an outgrower scheme. As the inventory data will be useful in assessing the system efficiency, some suggestions for system optimization based on the results will be examined.

1.7 Method

An LCA was conducted and the results evaluated using a sensitivity analysis. The benefit of LCA is that it recognizes not only the direct environmental impacts in a certain phase but also the indirect ones from e.g. production or waste handling. This is done by following the product from “cradle to grave”, that is from extraction of raw materials to disposal of waste. The impacts from all processes which the product passes through are allocated to the specific product and its function. Through the principle of system expansion it is even possible to account for indirect impacts that will occur far from the process, such as changes in fuel need for other processes when the studied process produce more surplus heat.

When assessing a product or service using LCA, impacts stemming from the life cycle are related to a functional unit, such as one liter of fuel. The results of an LCA study will in this way state the total life cycle impact of the functional unit of the product. An example of this can be total g CO_2 equivalents per liter of a biofuel. This way of assessing environmental impacts can be more relevant and fair than just looking at a certain phase within a life cycle.

An LCA can be used in many ways, the mayor one being comparison of different products. This is an important decision support for producers, consumers and policy-makers interested in environmental improvements. An LCA is also useful to the actors represented in the system as it can elucidate the most important steps in a products lifecycle with regard to environmental impacts. Actions to reduce environmental impacts can then be performed where they do the most good. Some environmental impacts are also closely related to costs, such as fuel or raw material use.

The first step in an LCA is defining its goal and scope. The formulation of this is however far from unambiguous. Three main questions to address are choosing functional unit, definition of system boundaries and choice of environmental impact categories (ICs). It is important to realize that the result of the study, a set of numerical values, is related to the goal and scope and does not represent the “whole truth”. The next step is to conduct an inventory analysis, which is collected data for all life cycle activities within the system boundaries defined. Once the inventory analysis is completed, the data can be attributed to the chosen IC, mentioned earlier. This is referred to as impact assessment. Common ICs are global warming potential (GWP), energy use, ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification- and eutrophication potentials. Finally, the results should be interpreted, evaluated and discussed. More information regarding LCA methodology can be found in Baumann and Tillman (2004) and ISO (2006).

1.8 Data acquisition

This report is based on a field study to the jatropha plantation in Luambala and Chikwetis area of operations around Lichinga, Mozambique. Scientific literature was used to find background information and to gain more knowledge of the jatropha production system. Some site specific data was not possible to acquire in the field study and instead data from scientific literature and handbooks has been applied.

Chikweti has kindly offered the authors an opportunity to study its operations. An oil press and a transesterification plant were accessible for investigation, but not yet operational. During the stay of five weeks at the site, life cycle data was acquired through measurements but mainly interviews with the employees.

2 Goal and Scope

The goal and scope of the life cycle assessment is presented in chapter two, including an introduction of the functional unit used. The flow chart of the analyzed system and its boundaries are presented and the reference system is described. The impact categories used; global warming potential, fossil energy use and water use are presented. The water use section also contains a comparison of water use indicators found in literature and a description of the water use indicator developed exclusively for this study.

Within this project, an LCA study was performed, where PPO production was studied with regard to its environmental impacts from “cradle to grave”, that is from preparing the plantationuntil the oil is combusted in an engine. Three major impact categories has been examined; fossil energy use, global warming potential and water use. The results of this study contribute to answering the question of whether jatropha can be a part of sustainable development in rural parts of developing countries.

2.1 Functional unit

All inputs and outputs of the jatropha production system are related to the main function of the system, which is to produce jatropha pure plant oil. The chosen functional unit (FU) is thereby one liter PPO. This unit is appropriate as it is the unit commonly used when purchasing and using liquid transport fuels. Other possible FUs are kWh or MJ from the oil or kWh or MJ of effective work in an engine from burning the oil. These units ease comparison of different fuels but are also less comprehensive for actors involved.

2.2 System boundaries and system description

An overview of the studied system is presented in a flow chart, see figure 2.1 below. For these processes theenvironmental impacts will be examined.

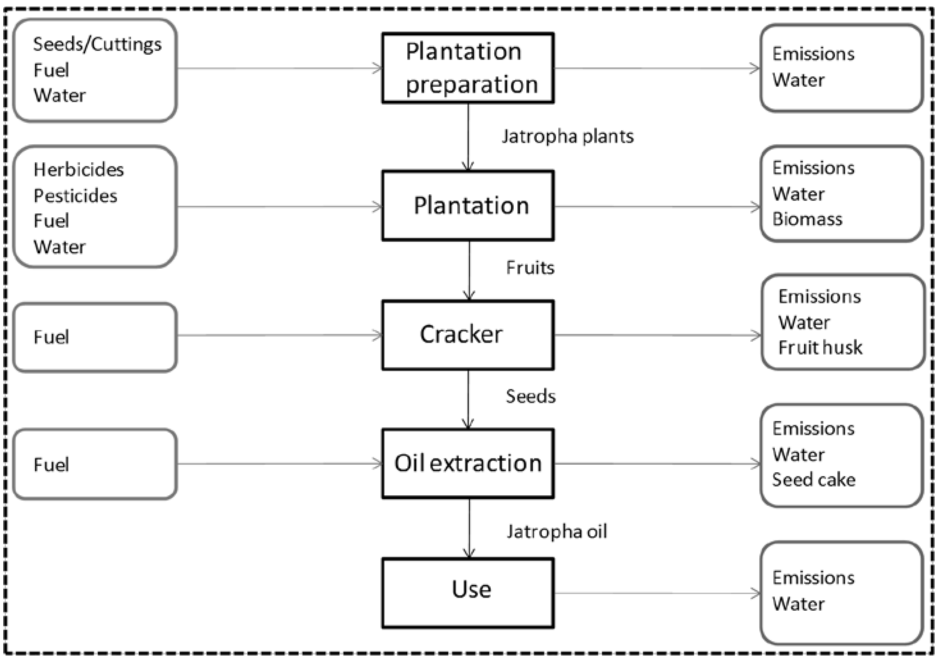

Figure 2.1. The flow chart of the jatropha production system studied in this LCA with inlets (left column) and outlets (right coloumn). The system boundary shows which processes that are included in this study. Note that transportations are included but not visualized in the figure.

The plantation preparation includes the jatropha nursery and all processes associated with the preparation of the field. It includes the planting of the seedlings and the transportation to the field. The plantation step in figure 2.1 includes the yearly activities at the field such as weeding, pruning and harvesting. The cracker process step describes the use of the cracking machine which removes and separates the seeds from the fruit husks. This step also includes drying of fruits and seeds. The oil extraction step describes the pressing of the dried seeds and purification of the oil into PPO. The studied system also includes the transportation from the location of oil extraction to the final destination and combustion.

The transformation of PPO into JME is not included in the examined system and the reason is that the production site in this case study appeared not to have developed this step yet. Although there are ambitions to produce JME in Lichinga, it is still far from being realized.

2.3 Reference system description

The reference system examines the use of fossil diesel in the same engines at Chikweti. The yearly consumption of fossil diesel at Chikweti is 600 000 L which they purchase from the gasoline company Peteromoc. Diesel purchase is one of the company's largest expenses and is one reason for why self-sustained production of diesel is desirable. Petromoc is most likely to import fossil diesel from Libya according to a local source. Fossil diesel can be produced from raw oil and this process is assumed in this case to take place in Libya. Raw oil extraction can be achieved with three different methods; onshore production, offshore production and enhanced recovery (Sheehan et al., 1998). The largest producing oil platform in Libya is the Bouri offshore field near the Libyan coast that can produce around 9500 m^3 raw oil per day (Wikipedia, 2011). This is assumed to be the origin of the fossil diesel used in Lichinga.

In the study by Sheehan and colleagues (1998), the energy used to extract the crude oil is assumed to be 7.5 percent more than the energy extracted. The emissions related to the extraction process are air emissions associated with combustion of natural gas (fuel used to run the processes), separators, gas turbines, venting, flaring and volatilization. The crude oil is then separated from gases, water and wastes which is carried out by combustion. These processes lead to air emissions. The extracted oil is then transported to the refinery (Sheehan et al., 1998). There are five big refineries in Libya. The oldest one, the Brega refinery near Tobruk, represents the refinery used in this study (Mbendi, 2011).

In the refinery the oil is processed into several refinery products, including diesel. The air emissions in this stage are associated with fuel combustion, process emissions and fugitive emissions. The emissions for the diesel production are allocated between the emissions for the gasoline production in the study by Sheehan and colleagues (1998). The diesel is then assumed to be transported by sea from Tobrok in Libya to the port of Beria or Nacala in Mozambique for transport by road to Lichinga. The diesel is assumed to be sold to Petromoc and finally used within the Chikweti company (Sheehan et al., 1998).

2.4 Fossil energy use

The use of fossil energy is an important contributor to environmental problems. Also, one big reason for growing jatropha in Lichinga is the difficulty and priceof transporting fossil fuels to this remote location. The impact category fossil energy use (FEU, sometimes also denoted embedded fossil energy or fossil cumulative energy demand) includes all direct and indirect fossil energy uses in the life cycle of a product that originates from a fossil energy source (Huijbregts et al., 2006, Arvidsson et al., 2011).

When measuring the use of fossil energy, only fossil resources are accounted for and no use of renewable energy is included (Arvidsson et al., 2011). In this study, the focus is on primary energy and in this impact category all sources of fossil energy will be included. Examples of uses of fossil energy in the system could be the use of fossil fuels at the fields and in machineries, use of electricity produced using fossil resources and use of materials and chemicals produced from fossil raw materials.

Apart from measuring just how non-renewable the so-called renewable jatropha PPO really is, the indicator FEU also illustrates the efficiency of the production system. As energy is the main product, an efficient system should not consume too much energy itself. The PPO is intended to be used in the production and will then of course lower the FEU of the fully operational system, but the indicator remains relevant as a measurement of the efficiency of the production chain.

2.5 Global warming potential

Emissions of greenhouse gases contribute to climate change. These gases are e.g. CO_2, methane (CH_4), chlorofluorocarbons, nitrous oxide (N_2O) and hydrocarbons. These gases absorb the infrared radiation from earth, thereby increasing the temperature of the atmosphere. Different gases absorb differently and the global warming potential (GWP) of a gas can be related to the heat absorption of CO_2. The GWP characterization factor (ChF) is defined as the ratio between the studied substances' increased heat absorption and the increased heat absorption that one kg of CO_2 is causing (Baumann and Tillman, 2004). These ChFs can be used to calculate the GWP of a product by adding up all the emissions of green house gases,see equation 2.1.

For jatropha, the assumed major contributors to GWP are N_2O emissions from the soil and CO_2 emissions from transports, field work operations and seed processing (Arvidsson et al., 2010, Achten et al., 2010). It is likely that other green house gases also are emitted, such as CH_4 from the soil and compost, but these will not be included in the study due to lack of data.The GWP of PPO production is, in this study, therefore calculated as

$$GWP = \sum_1^i \left(E_{CO_2 i} \times ChF_{CO_2} + E_{N_2O\ \ i} \times ChF_{N_2O}\right) \qquad (2.1)$$

where *i* is a phase in the product life cycle. The emission of a gas E is measured in [kg/L PPO] and the characterization factor (ChF) converts the emission into impact, see table 2.1.

For the fossil reference system, there are also some emissions of CH_4. Therefore, the GWP of diesel is calculated using equation 2.2.

$$GWP = \sum_1^i \left(E_{CO_2 i} \times ChF_{CO_2} + E_{N_2O\ \ i} \times ChF_{N_2O} + E_{CH_4 i} \times ChF_{CH_4}\right) \qquad (2.2)$$

Table 2.1. The GWP conversion factors for the time horizon 100 years developed by IPCC (2007).

Characterization factors	[kg CO2-eq / kg]
CO_2	1
CH_4	25
N_2O	298

2.6 Water use

Humans and ecosystems are dependent on water for biological functions but due to climate variations, water scarcity does exist in some parts of the world. Humans need water for personal use and for industrial processes and the sector that uses the majority of the world's resources of freshwater (86 percent), is the agriculture sector. To reduce the world's emissions of gases contributing to global warming, the production and use of bioenergy is highly promoted. There are however drawbacks with using farming fields for bioenergy production. The production of bioenergy crops can compete with food production and also the water use is of concern since water used for bioenergy crops cannot be used for food crops (Berndes, 2010). Water use is an important aspect considering bioenergy production and should not be neglected (Gerbens-Leenes et al., 2009).

How much water a crop needs depends on the climate, the type of crop and the growth stage. The climatic factors are sunshine, temperature, wind speed and humidity. The more sunshine, higher temperature, higher wind speed and lower humidity result in higher water demand (Brouwer and Heibloem, 1986)

2.6.1 Water sources and the hydrological cycle

The hydrological cycle describes the water movement above and below the surface and the main processes are precipitation, evaporation and the transport of vapour. The processes and their origins can be seen in figure 2.2.

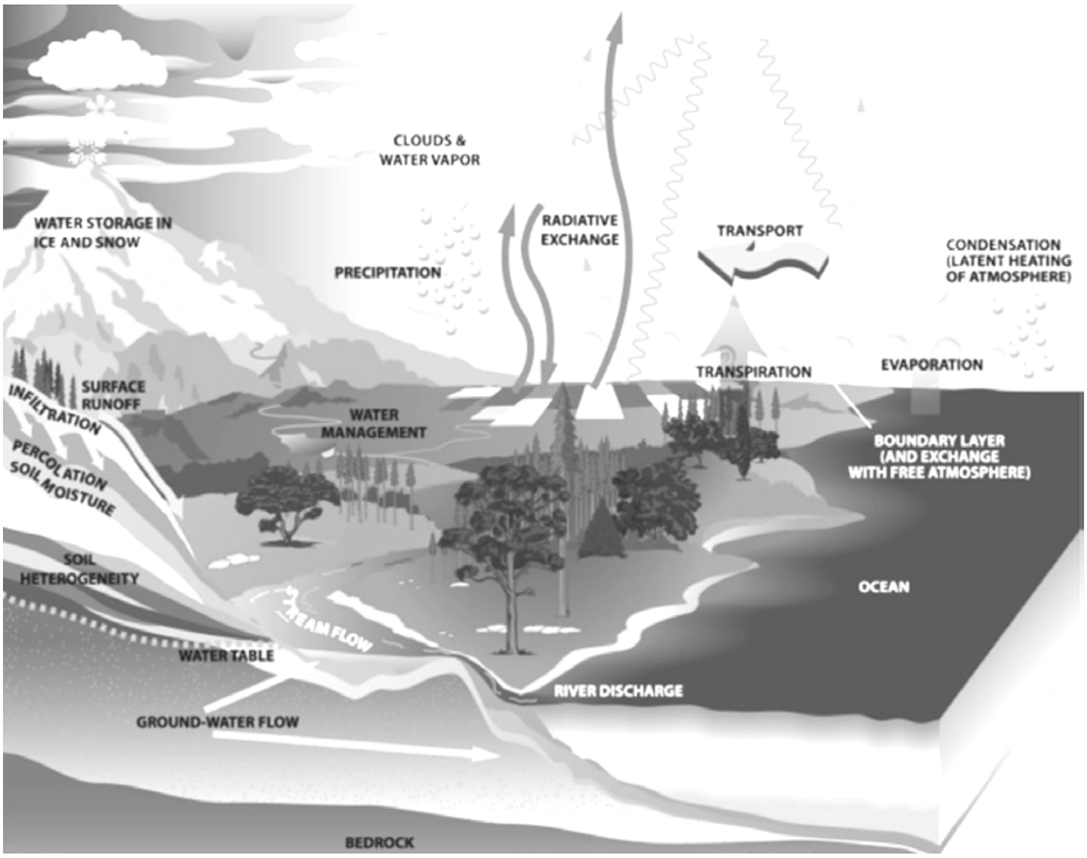

Figure 2.2.The hydrological cycle and the main processes of water (Blesgraaf, 2009).

The hydrological processes in figure 2.2 are on global scale but some of them also occur at local scale. These processes are of greater importance when assessing the water use in a local area like a jatropha plantation. The most important hydrological processes are described below.

Precipitation is a natural process that occurs when the water vapour in the atmosphere condensate and form droplets that falls to the ground. It could be rain, snow or hail. How much it rains in one area depends on the climate conditions and seasonal variations. Rain water can find different routes to the crop and is considered the most important source of water because all terrestrial water originates from precipitation. Rain, which is captured before, can runoff or be a part of subsurface processes are called interceptive precipitation or interception. It includes water that evaporate and transpirate in less than a day from the leaves and the soil surface. The part of the rain that is not interceptive infiltrates the soil layer and becomes soil moisture. Water in soil can either evaporate, be uptaken by the crop and transpirate through leaves of the plant, percolate to surface waters or contribute to the recharge of groundwater.

Evapotranspiration is a collected term that includes both evaporation and transpiration. When water gains energy, mostly from the sun, it is evaporated and enters the atmosphere as water vapour. Water can escape from the leaves of plants through the stomata due to gas exchange and this is called transpiration. The water in the top centimeters of the soil layer is not included in the term soil moisture because it evaporatesquickly. This is called soil evaporation and is part of the interception. Water that cannot infiltrate the soil is running off on the surface, a process called surface runoff. This occurs when the soil already is saturated or when the rate of precipitation is higher than the infiltration rate. This can cause water logging which affects jatropha plants negatively.

The largest reserves of freshwater are the groundwater reserves (Blesgraf, 2009). *Groundwater* is water that exists in aquifers beneath the surface. The aquifers can be either open or closed and how sustainable the use of groundwater is, depends on the hydrological cycle's ability to recharge the aquifer. *Surface water* includes all water reservoirs that exists on the earth's surface and includes rivers, seas, lakes, streams or water cisterns, see figure 2.2. The origin of this water is the surface runoff and precipitation (Owens, 2002).

2.6.2 Water sources considered in water use assessments

In an LCA, water use is not often assessed but recent reports highlight the importance to consider water use as an environmental impact. It is a new field and no standardized indicators for water use in a process or life cycle yet exists. Freshwater for human and ecosystem use originates from several sources and scientists have different views on these resources and how they should be handled in the calculations for water use. Where the water used in a process originates is important to consider because it affects the environment and ecosystems differently. A comparison of selected recent studies is presented in the next section.

2.6.2.1 Precipitation in LCA

There are significant variations in how precipitation is considered in different studies as discovered in the paper by Peters and colleagues (Peters et al., 2010). Owens (2002) argues that rainfall is a natural process that recharges other water resources and therefore should be considered as a renewable resource (Owens, 2002). Milá i Canals and colleagues agree with Owens as they see rain as a flow resource. But they add that if rain is withdrawn from one process it cannot be used for another and hence the use of rainwater may also be problematic (Milá i Canals et al., 2008).

Other scientists which have developed the water use indicator *water footprint* include the use of rainwater in the calculations and consider it as an actual use of freshwater. The part of the water footprint which accounts for the use of rainwater is called *green water footprint.* This indicator includes the part of the effective rainfall (the part of rainwater which is not runoff or directly evaporated but absorbed by the soil), uptaken by the crop that eventually evapotranspirates (Chapagain and Hoekstra, 2010). The concept of *virtual water* also includes precipitation when calculating the first approximation for water use of a crop, including rainwater and irrigation requirements as in the study by Zeitoun et al. (2009).

Peters and colleagues (2009) suggest that rainwater should be completely disregarded in water use assessment because it is a renewable source of water. They argue that rain cannot be used faster than it falls and should thus not be considered as extracted from its original course. They suggest that it is hard to predict if a studied industrial process affects the rainfall since precipitation and evaporation are natural processes. What needs to be considered is if the receiving water bodies of runoff water is affected anyhow by human use of rainwater. Rain is according to them the most sustainable water resource. The reason for the varying results in LCA studies which include water use, they suggest, is how the rainwater is considered. It is hence important to find a good way to treat precipitation in LCA when it comes to water use. They argue that rainwater can be of importance when looking at a system which includes several nations, otherwise it should be neglected in the calculations (Peters et al., 2009). Berndes believes that if rainwater is used in a process, downstream water resources that are depended in surface runoff to recharge can be affected. Otherwise the use of rainwater prevents the use of other, scarcer types of water, and should therefore be considered beneficial (Berndes, 2010).

2.6.2.2 Groundwater in LCA

Groundwater is water which is stored in open or sealed aquifers below the earth´s surface. Also for this water resource, there is a discussion whether it could be considered a sustainable resource or not.

Owens makes a distinction between open and sealed aquifers, where sealed are considered as deposit/fossil water (Owens, 2002). Milá i Canals and colleagues consider groundwater as a fund of freshwater and not as deposit water. When groundwater is used in a process and then returned to its origin, the only losses considered are the evaporate losses (Milá i Canals et al., 2008). In the concept *water footprint* the groundwater use is calculated and included in the *blue water footprint,* which is a part of the total water footprint (Chapagain and Hoekstra, 2010). Peters and colleagues (2009) observed that many studies include the use of groundwater and agree that this is important. If the used groundwater is returned to its origin, the returned water's quality must be examined and considered (Peters et al., 2009). Bulsink and colleagues (2009) made a calculation of the water footprint of crop products in Indonesian provinces and even if their result showed that green water is the largest factor, they think that blue water affects the environment more because it originates from groundwater and surface water which are less sustainable (Bulsink et al., 2009).

2.6.2.3 Surface water in LCA

Surface water is water which exists on the earth's surface and could be a river, lake, stream or water storage.

According to Owens, the surface water is recharged by rainwater and is considered renewable but maybe not sustainable, and is hence considered a fund resource of water. The quality of the returned water is of greater importance than the actual amount of water used. It is also important to consider different uses of surface water and if the water in a process is returned to its original source after use or moved to another location (Owens, 2002). Milá i Canals and colleagues consider surface water as a flow resource and discuss the importance of returning the water to its original basin with the same quality as it was discharged. They believe that water only is consumed if it is evaporated and thus surface evaporation should be considered in an LCI (Milá i Canals et al., 2008). In the concept of *water footprint,* the surface water is included in the blue water footprint (Chapagain and Hoekstra, 2010).

2.6.3 Indicators of water use in LCA

To assess water use in an LCA, indicators of water use are needed, and there have been many varying indicators proposed in literature.

Methods for assessing water use of bioenergy crops are under development and accurate indicators are needed. Jatropha is claimed by proponents to use relatively small amounts of water and is considered a water efficient crop (Heller, 1996). But its water use still needs to be assessed properly. There have been a few studies made on the water use of jatropha but they show diverse results (see for example Gerbens-Leenes et al. 2008, Jongshaap et al. 2009, Hoekstra et al. 2009a) and should thus be further investigated.

As we have seen, water use indicators presented in literature vary in for example how they assess quantity of water used and how the quality of the returned water is handled.A literature study has been conducted and selected water use indicators in literature have been investigated, described and compared.

In table 2.2, the selected water use indicators have been presented.They focus on different aspects of water use, representing the views of the different authors. Table 2.2 illustrates the different aspects, or categories, that can be included in an indicator. The categories are precipitation, ground water, surface water, evapotranspiration, human health, ecological health, water quality and water quantity. If the indicator addresses or includes a category, the column is marked with an ‘x’, see table 2.2. The chosen water use indicators are further described in the section below or in literature.

Table 2.2. Comparison of water use indicators proposed in literature.

Indicator	Precipi-tation	Ground water	Surface water	Evapo-transpiration	Human health	Ecological health	Water quality	Water quantity	Author(s)
Water resources per capita (WRPC)		x	x			x		x	Milà i Canals et al. (2008)
Water use per resource (WUPR)		x	x			x		x	
Water stress indicator (WSI)						x		x	
Abiotic depletion potential (ADP)		x	x			x		x	
In-stream water use indicator			x					x	Owens (2002)
In-stream water consumption indicator		x	x	x				x	
Off-stream water use indicator		x	x					x	
Off-stream water consumption indicator		x	x	x				x	
Off-stream water depletion indicator		x						x	
Eutrophication		x	x			x	x		
Dissolved Oxygen Demand			x			x	x		
Pathogenic Microorganisms		x	x		x	x	x		
Colour and Turbidity			x			x	x		
Suspended solids		x	x			x	x		
Toxicity		x	x		x	x	x		

Table 2.2 continued. Comparison of water use indicators proposed in literature.

Indicator	Precip-itation	Ground water	Surface water	Evapo-transpiration	Human health	Ecological health	Water quality	Water quantity	Author(s)
Green water footprint	x			x				x	Gerbens-Leenes et al. (2009)
Blue water footprint		x	x	x				x	Gerbens-Leenes et al.(n.d.)
Grey water footprint					x	x	x	x	Berger and Finkbeiner (2010) Chapagain and Hoekstra (2010) Bulsink et al. (2009) Hoekstra et al. (2009a)
Water use	x	x	x	x			x	x	Peters et al. (2010)
Water use efficiency		x	x					x	Abou Kheira and Atta (2008)
Virtual water (VW)	x	x	x	x	x	x		x	Milà i Canals et al. (2008) Zeiton et al. (2009) Gerbens-Leenes et al. (2009) Aldaya et al. (2009)

Table 2.2 continued. Comparison of water use indicators proposed in literature.

Indicator	Precipi-tation	Ground water	Surface water	Evapo-transpiration	Human health	Ecological health	Water quality	Water quantity	Author(s)
In-stream freshwater degradative use		x	x			x	x		Berger and Finkbeiner (2010)
In-stream freshwater consumptive use		x	x	x		x		x	
Off-stream freshwater degradative use			x			x	x		
Off-stream freshwater consumptive use		x	x	x				x	
Water inventory		x	x					x	
EDIP	x	x	x	x				x	
CExD and CEENE		x	x					x	
Eco-factor		x	x					x	
Water quantity		x	x					x	
Water quality					x	x	x		
Freshwater deprivation for human uses		x	x				x	x	
Human health damage assessment-agricultural		x	x		x			x	
Human health damage assessment-domestic		x	x		x		x		
Ecological damage of groundwater extraction		x				x	x	x	
Damage on aquatic ecosystems-use from dams			x			x	x		
Impact assessment of freshwater consumption		x	x		x	x	x		

The indicators presented by Milá i Canals and colleagues are divided into freshwater ecosystem impact (FEI) and freshwater depletion (FD). The FEI is defined as the volume of water ('ecosystem-equivalent') that is likely to affect ecosystems and included in this indicator isthe *water resource per capita* (WRPC) which determines water stress, scarcity or absolute scarcity. It only accounts for human direct use (drinking) and relates the total amounts of water used to the total available resources. Also included in the FEI isthe *water use per resource* (WUPR) which highlights the percentage of withdrawn water from natural water bodies and includes how much water is left for in-stream usage. It also includes potential damage on aquatic ecosystems. Milá i Canals also present an indicator developed by Smakthin and colleagues (2004) which first calculates the *environmental water requirements* (EWR) for river basins and comparing EWR with the water use result in the *water stress indicator* (WSI). The FD midpoint indicator only includes the characterization factor *abiotic depletion potential* (ADP) which is a baseline method for calculating the abiotic resource depletion which includes the depletion of a water resource. The ADP depends on the extraction rate of a resource, the reserve and the deaccumulation rate of a reference resource (Milá i Canals et al., 2009).

The indicators proposed by Owens (2002) are divided into the categories *water quantity* and *water quality*. The indicators included in water quantity are divided into several water resource uses. The *in-stream water use indicator* refers to the quantity of water used for hydroelectric generation or water transport. The *off-stream water use indicator* assesses the surface withdrawals from sustainable resources and returned to its origin or returned to another source of surface water. The *off-stream water consumption indicator* includes evaporative losses and other losses of groundwater and surface water and transfers to another water basin. The *off-stream water depletion indicator* indicates the withdrawal of water from already unreplenished groundwaters. Other indicators presented by Owens can be found in the paper (Owens, 2002).

Peters and colleagues suggest a simple indicator called *water use* where the most important thing to consider is the origin and the quality of the water, whether it is returned to its origin and the extraction rate. In their study they made an input-output analysis and grouped transferred flows and funds of water. The evaporated water has the best quality, next is the runoff and the lowest quality has the excreted water and discharges to sewers. The water removed from the environment which enters a product is alienated water. Their category *net use* includes *moderate quality, low quality* and *alienated flows*. They use hydrological models to estimate water use and the most significant flows were the rainfall, evapotranspiration, deep drainage and runoff (Peters et al., 2010).

The concept of *virtual water* was developed in the early 1990s by professor John Anthony Allan and is an indicator of how much water is needed to produce a product, not only including the water content of the finished product (Allan, 1998). The water footprint, which is further described in next section, was developed from this concept and has been described in many scientific papers and has more or less replaced the virtual water concept.

Berger and Finkbeiner (2010) present several other water use indicators used in scientific literature, but they will not receive more attention here.

2.6.4 Water use indicators used in this study

In this study, two indicators have been chosen to assess the water use in the jatropha production system and the reference system. The two indicators are the *water footprint* and the *local* *hydrological cycle deviation* where the second one is developed exclusively by the authors for this study. The indicators are described in this section.

2.6.4.1 Water Footprint

A popular indicator of water use is the *water footprint* and since it is widely used, this indicator has been applied in this study. The *water footprint* (WF) is a development of the concept virtual water, introduced in the early 1990s by Professor John Anthony Allan. The water footprint was then introduced in 2002 by Arjen Hoekstra (Berger and Finkbeiner, 2010). The concept includes both direct and indirect use of water in a process and often includes the green WF, blue WF and grey WF. They can be calculated separately but can also be summarized into a total WF (Hoekstra et al., 2009a). The organization *Water Footprint* has a large list of water footprints of bioenergy crops but has not yet studied the water use of jatropha which make the use of this indicator in the study more interesting (Mekkonen and Hoekstra, 2010).

The green WF (WF_{Green}) is an indicator mainly used in agriculture and forestry and is a measurement of the amount of rain water used in an industrial process (Hoekstra et al., 2009a). It refers to the amount of effective rainfall uptaken by a crop(CWU), which has evapotranspirated during crop growth. The yield of the crop is important as the WF_{Green} also includes the amount of rainwater as a share of all water ending up in the final product (Gerbens-Leenes et al., n.d)

The green WF for a crop can be calculated with equation 2.3,

$$WF_{Green} = \frac{CWU_{Green}}{Y} \qquad (2.3)$$

Where WF_{Green} is the green water footprint [m^3/ton of crop], CWU_{Green} is the crop green water use [m^3/ha] and Y is the crop yield [ton/ha of crop]. When studying an agricultural system, some measurements of the crop, soil and climate are needed. The CWU can be calculated by summarizing the evapotranspiration of the crop during the whole growing period (Hoekstra et al., 2009a).

The blue WF (WF_{Blue}) includes the human consumption of fresh ground- and surface water, but it also includes the use of deposit (fossil) water. Included processes are evaporative losses, water integrated in products and when water is moved from its origin and returned but in another time period. The evaporation accounts for the biggest part of the losses when using blue water. The blue WF can be calculated in the same way as the green WF (equation 2.3), but instead using the crop water use of blue water (Hoekstra et al., 2009a).

In agricultural processes, the blue WF is typically the amounts of irrigation water (surface-, ground- and deposit water) that has evapotranspirated during crop growth (Gerbens-Leenes et al., n.d.).

The grey WF differs from the green and blue WF because it focuses on pollution of process water. It is defined as the amount of water needed to dilute the pollution to a concentration which meets the local quality standards. On a field, different chemicals such as herbicides, pesticides and fertilizers could be used and might leach to the surrounding nature. The grey WF can be calculated with equation 2.4.

$$WF_{Grey} = \frac{(\alpha \times AR) / (C_{max} - C_{nat})}{Y} \qquad (2.4)$$

Where WF_{Grey} is the water footprint [m^3/ton], α is the leaching factor, *AR* is the chemical application rate per hectare of for example fertilizers [kg/ha], c_{max} is the maximum acceptable concentration, which is the ambient water quality standard for the specific pollutant [kg/m^3] and c_{nat} is the natural concentration in the receiving water body [kg/m^3]. *Y* is again, the crop yield [ton/ha] (Hoekstra et al., 2009a).

In this study, only the green WF and the blue WF will be assessed due to time constraints and lack of data and thus:

$$WF_T = WF_{Green} + WF_{Blue} \qquad (2.5)$$

2.6.4.2 Local hydrological cycle deviation

In this study, an indicator of water use focused on the resource aspect and the perspective of a local hydrological cycle has been developed. The local system is defined according to each case which in this case is the Luambala farm. Resources in general can be divided into *flow*, *fund* and *deposit* (Wall, 1990). Although water quality is an important aspect (Owens, 2002), only the quantity of used water and its origin (deposit, fund, flow) is considered in this indicator. The indicator was developed in order to find new perspectives to the complex area of water use assessment. The new aspects considered in this indicator were introduced due to lack of area perspectives in this field.

The indicator of water use developed is the *local hydrological cycle deviation* (LHCD)which is a sum of the *flow*- (W_{Fl}), *fund*- (W_{Fu}) , and *deposit water resource use* (W_D). Water use is here defined as water removed from the local hydrological cycle. The three different sub-indicators can be presented separately or summarized into LHCD according to equation 2.6,

$$\mathrm{LHCD} = W_{Fl} + W_{Fu} + W_D \qquad (2.6)$$

Where *LHCD* is the local hydrological cycle deviation [m^3/unit product], the W_{fl} is the flow water use [m^3/unit product], W_{Fu} is the fund water use [m^3/unit product] andW_D is the deposit water use [m^3/unit product]. The indicator and sub-indicators are described below.

The water assessment indicator is based on studying the hydrological cycle at a local level and all hydrological processes that occur locally. When water is incorporated into a unit of product which is removed from the local system, this water is considered as used.All losses, such as evapotranspiration losses, occurring in the defined local system are not accounted.

When studying an agricultural system, as the cultivation of jatropha in this case, the evaporative losses due to soil evaporation and evapotranspiration is not included in the LHCD since a planted tree is assumed to affect the local hydrological cycle as much as a naturally occurring tree, in accordance with the view of Peters et al. (2010). In cases where the crop factor differs from the natural vegetation this assumption is a drawback of this indicator which should be taken into consideration.

Flow water use (W_{Fl}) describes the resource of water which is continuous and is constantly refilled. It includes rainwater and large rivers, which mean that withdrawal of these kinds of water, do not affect the environment or decrease the availability for other users. The W_{Fl} is considered as the most sustainable source of water, considering that there is no risk of depletion. The calculations are based on the amounts of flow water in m^3/unit product that is taken away from the local production system. In the jatropha production system, this means that the water content of the fruits which are harvested is considered as a loss because it is taken away from its origin. If the fruit should be left to decompose at the plantation, some of the water content would evaporate in the local system. Fruits that are harvested and removed from the field cannot be a part of the local cycle and is considered as a human use of water. The W_{Fl} is thus a sum of the flow water incorporated in the product ($W_{p,Fl}$), the flow water contained in residues removed far away from the local hydrological cycle ($W_{Res,Fl}$) and the water evaporated from biomass during handling and transportation occurred far away from the local system ($W_{Evap,Fl}$). The flow water use for an agricultural system, such as the jatropha production system, can be calculated with equation 2.7.

$$W_{Fl} = W_{P,Fl} + W_{Res,Fl} + W_{Evap,Fl} + W_{Eq,Fl} \qquad (2.7)$$

Where $W_{Fl}$is the total flow water use [m^3/unit product], the $W_{p,Fl}$ is the amount of flow water incorporated in the product [m^3/unit product], $W_{Res,Fl}$ is the flow water content in the residues removed from the system but not incorporated in the product, assumed that the residues are not returned to the local system [m^3/unit product]. $W_{Evap,Fl}$ is the amount of evaporated flow water from other biomass removed from the system far away from the local system according to the chosen definition [m^3/unit product].$W_{Eq,Fl}$is the amount of flow water used when producing equipment, materials and energy used within the system [m^3/unit product]. The equipments are produced within another local hydrological cycle, e.g. a mine or a factory.

Fund water use includes use of refillable groundwater and surface waters. Fund water use (W_{Fu}) is water taken from open aquifers and surface water which can be refilled by rainwater but is not considered as a flow resource because it is not guaranteed that it is available for other users. Use of water withdrawn from these sources can affect the hydrological cycle since the return of the water is not in the same temporal period or of not the same quality. Fund water use is therefore not as sustainable as the flow water use. In an agricultural system the use of fund water often occurs in the case of irrigation requirements using surface water or groundwaters. Applied water withdrawn from a nearby river is assumed to be used by the crop to a certain extent, but most of the irrigation water is evaporated from the plant and soil and returned to the local hydrological system and should be neglected. The only water use that should be considered is the share of the fund water contained in the unit removed from the local system and thus be calculated as the W_{Fu} , using equation 2.8 with the same unit [m^3/unit product].

$$W_{Fu} = W_{P,Fu} + W_{Res,Fu} + W_{Evap,Fu} + W_{Eq,Fu} \qquad (2.8)$$

Where $W_{Fu}$is the total fund water use [m^3/unit product], the $W_{P,Fu}$ is the amount of fund water incorporated in the product [m^3/unit product], $W_{Res,Fu}$ is the water content in the residues removed from the system but not incorporated in the product, assumed that the residues are not returned to the local system [m^3/unit product]. $W_{Evap,Fu}$ is the amounts of evaporated water from the units removed from the system far away from the local system [m^3/unit product].$W_{Eq,Fu}$ is the amount of fund water used to produce equipment, materials and energy used,[m^3/unit product] .

In the case of transporting fund water great distances or applying the water in a different time period, the evapotranspiration losses should be considered and then the W_{Fu} would be the same as the amounts of removed/applied water.

Deposit water use is also termed fossil water and includes water reserves like closed aquifers and groundwater which cannot be refilled by the hydrological cycle. The deposit water use (W_D) describes the amounts of water used (removed from the local system) from these reserves. It is the least sustainable use of water and can be calculated by the same principle as the *flow water use* and the *fund water use*. The equation 2.9 is used to calculate W_D.

$$W_D = W_{P,D} + W_{Res,D} + W_{Evap,D} + W_{Eq,D} \tag{2.9}$$

Where W_D is the total deposit water use [m^3/unit product], the $W_{p,D}$ is the amount of deposit water incorporated in the product [m^3/unit product], $W_{Res,D}$ is the deposit water content in the residues removed from the system but not incorporated in the product, assumed that the residues are not returned to the local system [m^3/unit product]. $W_{Evap,D}$ is the amounts of evaporated deposit water from the units removed from the system far away from the local system [m^3/unit product].$W_{Eq,D}$ is the deposit water used to produce the required equipment, materials and energy in the system in the unit [m^3/unit product].

3 Inventory of the Jatropha production system in Luambala

The inventory chapter introduces the factors used for calculations and presents all relevant equations used. The presentation of the calculations is divided into the different parts of the jatropha system in Mozambique; plantation preparation, plantation, oil processing and use. Each part is shortly described and the results are presented in a summarized table. The calculations for the reference system are also presented in this section.

In the northern province of Niassa in Mozambique, 80 km from the province capital Lichinga lies the jatropha plantation. It is close to a tarmac road, making transportation easier than in other parts of Niassa. Luambala Jatropha Lda, a subsidiary of Chikweti, currently has a license to grow agricultural crops on a 1000 ha area between the road and the northern bank of the Luambala river. It was set up in 2006 with the aim of producing a safe and cheap supply of biodiesel for Chikweti.

The long term goal is to cultivate 10 000 ha of jatropha but so far less than 500 ha has been planted, and not only with jatropha. In 2011, the company also planted commercial crops such as maize and soya. Two areas of jatropha have been planted to this date, one is 208 ha and the other is 66 ha. The smaller plantation, which lies far away from the farmhouse, unfortunately suffers from great problems with termites and other pests as well as erosion due to poor planning while planting. These 66 ha are not taken care of and will not be harvested, but will be replanted.

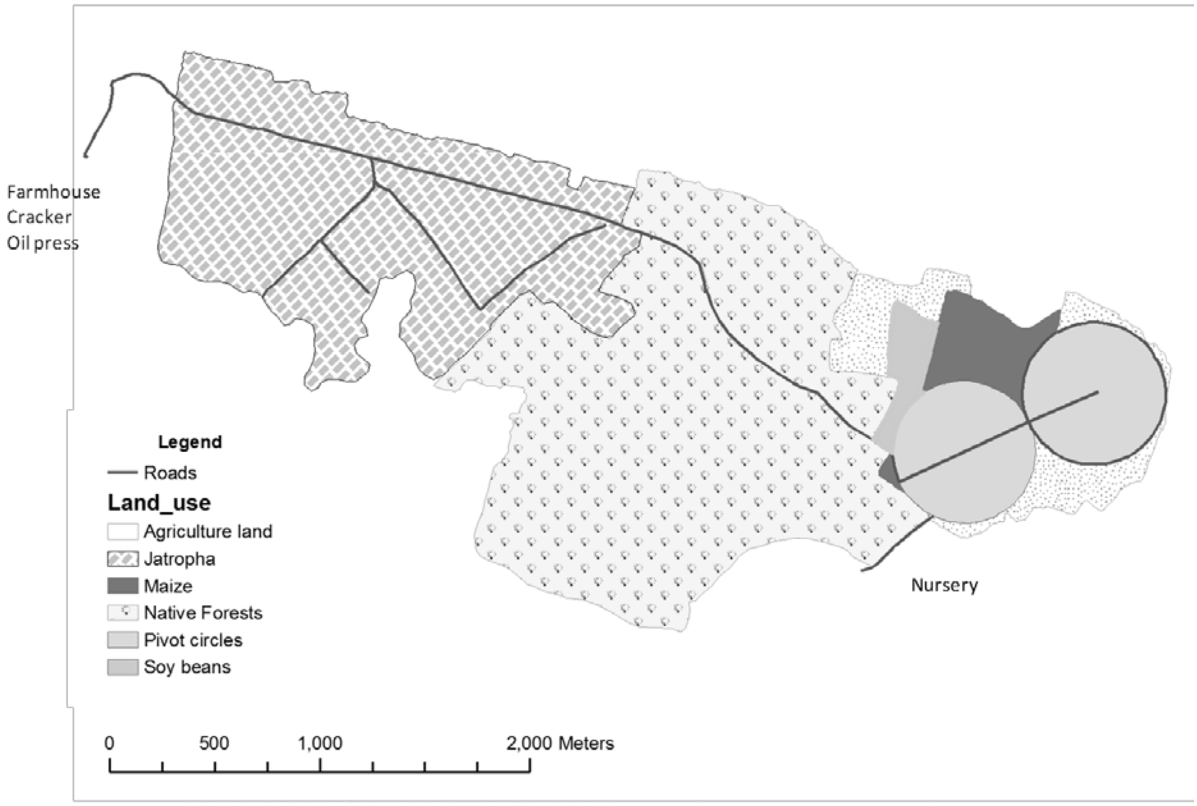

Figure 3.1. The main plantation of Luambala Jatropha Ltd in 2010. There were at the time 208 ha of jatropha.

The area is located 900 meters above sea level and receives 900-1400 mm of rain annually. It is hot and humid all year round with the rainy season reaching from approximately November to April. The exact length of the rainy season, however, varies considerably. The soil of the area varies from red and black clay soils where the jatropha grows well and sandy soils with very little organic material on the top, where plant growth is very poor. In some places, the soil is waterlogged after the heavy rains of the rainy season, which reduces plant growth.

3.1 Basis for calculations

Here, basic parameters such as yield and conversion factors are estimated. Production of jatropha oil is still in the early development phase. When the field study was conducted, the oil press was not yet operational, standard methods for cultivation and processing was not established and the second harvest was taking place. The system was in many ways immature. To be able to carry out a life cycle inventory (LCI), a scenario was constructed which will serve as a basis for the calculations. This scenario is constructed mostly on current activities at Luambala but also on planned changes in the system as well as estimates by the authors regarding the future functionality of the production system. The most notable assumptions are those regarding the future yield and the functionality of the oil press and the nursery.

It is however not assumed that any PPO is used as a fuel in the production chain, although this is the ultimate goal of Chikweti. This is because the functionality of the PPO in the various machines is not known and production is currently much lower. The use of PPO within the production system will however be discussed in section 5.4.

3.1.1 Yield

The jatropha seed yield varies a lot between different studies and depends on plant genetics, local climate and field operations. Examples of differing yields found in literature are presented in table 3.1.

Table 3.1. Examples of varying jatropha seed yields found in literature using different units.

Study	Dry seed yield [tons dry seed/ha]	Country
Francis et al.(2005)	0.5-12	India
Nazir et al. (2009)	1.5-2.5	Nicaragua
Prueksakorn and Gheewala (2008)	12.5	Thailand
Abou Kheira and Atta (2008)	0.8	Egypt
Lam et al.(2009)	0.4-12	Undefined
	2.382 (non-fertile)	Undefined
	5 (fertile)	Undefined
Achten et al. (2008)	0.4-12	Undefined
	2 - 3 (semi-arid, wasteland)	Undefined

Because the bushes at Luambala have not yet reached their expected yield, the future yields are calculated using data of last year's harvest and models. As a basis for calculations, the plantation is assumed to cover 450 ha by 2013 and the number of bushes per ha will constantly be 2500.The plantation may expand more after this, but this will not be a part of the scenario in this LCI. Every bush is assumed to stand for 30 years, which is the productive life span predicted at Luambala, although some authors claim it is rather 20 years (Achten et al., 2008, Prueksakorn and Gheewala, 2006). The yield is assumed to increase for the first few years until its maximum yield is reached. This development is calculated using Richard's curve, also called the generalized logistics curve, which is often used in growth models including forest growth (Nielsen, 2009). The general formula is presented in equation 3.1

$$Y_x = A + \frac{(C-A)}{(1+Te^{-B(x-M)})^{1/T}} \quad (3.1)$$

Where Y_i is the yield at year *x*, *A* is the lower asymptote, *C* is the upper asymptote (The maximum yield), *M* is the time of maximum growth, *B* is the growth rate and *T* is the year at which asymptote maximum growth occurs.

In the study by Flemming Nielsen for FACT/ADDP (2009), the maximum yield for a project in Mozambique was modeled by using Richard's curve. The parameters where chosen by simulating the yield based on a case of jatropha plantation in Paraguay. The parameters where calculated by Nielsen and are presented in table 3.2. These parameters where chosen in the modeling in this study. First the maximum yield, C, was calculated according to last year's harvest in Lichinga using equation 3.1. It was calculated that C is here 1500 kg dry seed/ha. In the study by Nielsen however, the C was calculated to be 3900 kg dry seed/hameaning a higher yield was possible under those circumstances.

Table 3.2. The parameters used to model the variations in yield during a lifetime of a jatropha tree (Nielsen, 2009).

Parameters for Richard's curve	Value
A	0
C	1500 (calculated)
M	6.9
B	4
T	7
X	1

Using the parameters and modeling the variations in yield with a jatropha tree's age, a curve was obtained and is presented in figure 3.2.

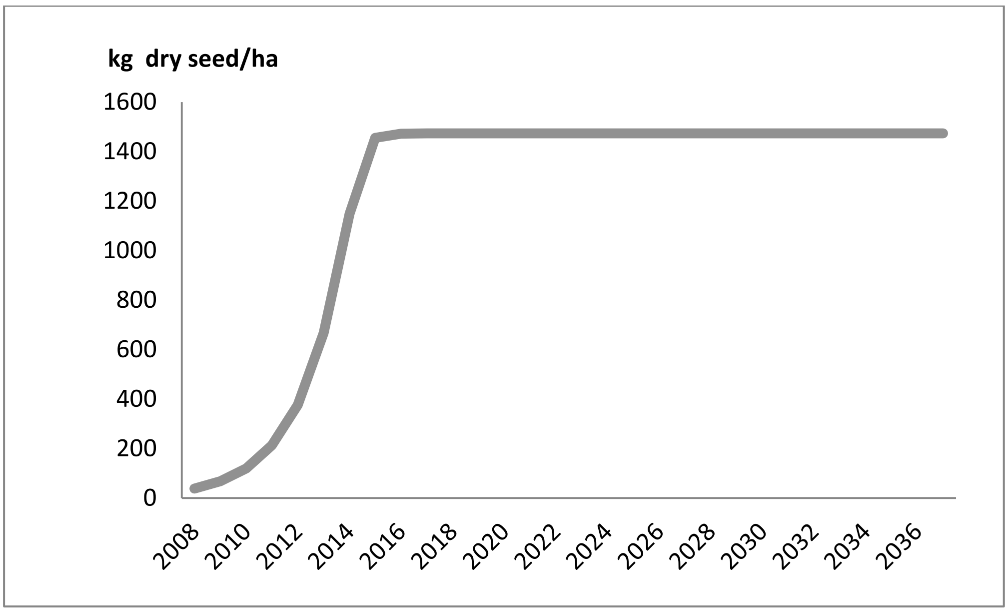

Figure 3.2. The calculated variations of yield during a jatropha tree's life, using Richard's curve.Thecalculations are based on 2010's harvest.

The yield increases at young age, but is then constant on a maximum yield of 1473 kg dry seeds/ha for Luambala case until it reaches 30 years of age.

The yearly averageyield (*Y*) is an important factor because all inputs and emissions during the agricultural stage are related to this value. This is calculated using the following equations:

$$Y = \frac{Y_{Tot}}{A_{Tot}} \quad (3.2)$$

where

$$Y_{Tot} = \sum_{x=1}^{36} Totalyieldyearx \quad (3.3)$$

$$A_{Tot} = \sum_{x=1}^{36} Totalareayearx \quad (3.4)$$

The area is assumed to be expanded yearly the first years to reach a total area of 450 hectares.Y_{Tot} and A_{Tot} is calculated summarizing 36 years because the last part of the plantation is planted six years after the first part is planted and also cut down six years later, resulting in a plant life of 30 years.The average yield (*Y*) was calculated to 1216 kg dry seeds/ha.

3.1.2 Conversion factors

Most emissions are not directly related to the final product PPO. As an example, when pumping water to the nursery it is impossible to foresee how this will affect the amount of produced oil. But the activities are indirectly related, which can be illustrated by mathematical expressions. In the coming calculations, several conversion factors (CF) are used to present any emission related to the functional unit. By multiplying an emission per unit by the appropriate CF, the impact is derived as emission per literof PPO.

When determining the CFs it is usually easiest to begin with the final product and count backwards along the production chain. The first CF represents the conversion of kg dry seed which enters the oil press, into L PPO that is the final product and is calculated with equation 3.5.

$$CF_{kgdryseedtoLPPO} = \frac{\rho_{PPO}}{Oilcontent \times RF \times \left({}^{LPPO}/_{Lunfilteredoil} \right)} \quad (3.5)$$

The unit of $CF_{kg\ dry\ seed\ to\ L\ PPO}$ is [kg/L], which means that if it is multiplied with a factor with the unit emission/kg dry seed, the result will be impact/L PPO. ρ_{PPO} is the density of PPO [kg/L]. The three factors in the denominator of equation 3.5 are dimensionless and account for the fact that not all the mass of the seed is PPO. *Oil content* is the total fraction of oil in dry seed, according to Achten et al. (2008) 0.34. The oil press recovery factor (RF) is 0.8 for this type of press and after filtration or other purification 0.76 PPO remain, according to Bereens and van Eijck (2010).

This CF is then used to calculate CFs for upstream processes.

$$CF_{HatoLPPO} = \frac{CF_{kgdryseedtoLPPO}}{Y} \quad (3.6)$$

$$CF_{Ha(once)toLPPO} = \frac{CF_{HatoLPPO}}{30} \quad (3.7)$$

Equation 3.6 converts impacts from impact/ha into impact/L PPO by having the unit [ha/kg] and accounts for the amount of dry seed harvested from each ha every year. The factor 30 in equation 3.7 accounts for activities that occur once during the thirty year life cycle of the jatropha bush. These two CFs have the same unit but should be used to convert impacts from different phases in the Jatropha production system. $CF_{Ha\ to\ L\ PPO}$should be used for the annual activities of the plantation phase whereas $CF_{Ha\ (once)\ to\ L\ PPO}$, which has a lower value, is used for the one time plantation preparation.

3.1.3 Emission factors

The burning of a fuel or production of a chemical often gives rise to emissions related to the amount of the fuel or chemical. These emissions are calculated by multiplying the amount used by a so called emission factor (EF). The EFs are used to characterize certain resource use into an impact category, whereas CFs are used to relate an emission to the functional unit.

The EFs are either acquired from scientific literature or calculated, such as in equation 3.8.A list of the EFs used presented in table 3.3 and 3.4.$EF_{Diesel\ FEU}$and $EF_{Diesel\ GWP}$ are also calculated for the fossil reference system, but those numbers are not used in other calculations.The emission factors retrieved from literature are assumed to be as good an approximation as the calculated values.

For tractor transport at the farm the EF is calculatedby assuming an average speed (v_A) of 10 km/h, an average load (m_A) of two tons and where $D_{Tractor}$ is the diesel consumption, 5.5 L/h

$$EF_{Tractortrsp} = \frac{EF_{Diesel} \times D_{Tractor}}{v_A \times m_{Average}} \qquad (3.8)$$

Table 3.3. The emission factors for fossil energy use (FEU) used in the coming equations.

Emission factor	Description	Unit	Value	Reference
$EF_{Diesel\ FEU}$	Consuming diesel, from well-to wheel	MJ/L	43	NTNcalc, n.d.
$EF_{Tractor\ trsp\ FEU}$	Transport by tractor	MJ/t km	11.8	
$EF_{Medium\ truck\ trsp\ FEU}$	Transport by medium heavy truck	MJ/t km	2.67	NTNcalc, n.d.

Table 3.4. The emission factors for global warming potential (GWP) used in the coming equations.

Emission factor	Description	Unit	Value	Reference
$EF_{Diesel\ GWP}$	Consuming diesel, from well-to wheel	Kg CO_2 eq/L	2.9	NTNcalc, n.d.
$EF_{Tractor\ trsp\ GWP}$	Transport by tractor	Kg CO_2eq/t km	0.80	
$EF_{Mediumtruck\ trsp\ GWP}$	Transport by medium heavy truck	KgCO_2 eq/t km	0.18	NTNcalc, n.d.

3.2 Plantation preparation

Jatropha is a perennial plant with a predicted productive period of 30 years. This means it is convenient to present activities and their impacts according to if they are performed every year or just a single time, such as planting.

3.2.1 Clearing of land

Surrounding the plantation is degraded natural forest with dense undergrowth. Most valuable trees have been removed for domestic use. Fires are very common during the dry season, hence only resilient tree species such as Masuku and Acacia remain. Although these give fruits, they are not considered valuable because they are not suitable for charcoal production or as construction material. In 2011, 100 ha will be cleared in order to expand the jatropha plantation. Within a year or two, jatropha will be planted where there are currently other crops, resulting in a total area of 450 ha of jatropha. The first year or two, when the jatropha is still small, there are plans of intercropping with soya. The soya fixates some nitrogen and carbon and can also give cash revenue if sold at the local market.

The forest is cleared manually, the trees are felled and the stumps are dug up to prevent Masukus regrowth. It takes 2-3 months to clear one hectare. Since the lumber is not valuable, it is burnt to give nutrients to the ground. It is considered good practice to save some of the big trees, but few big trees exist due to local utilization of the forest and the many fires.

Before planting, a tractor is used to make small terraces on which the seedlings are planted. The fossil energy use and global warming potential per liter PPO from this activity is calculated byequation 3.9.

$$I_{Terrace} = D_{Tractor} \times t_{Terrace} \times EF_{Diesel} \times CF_{Ha\ (once)\ toLPPO} \quad (3.9)$$

Where$I_{Terrace}$ is the impact of making the terraces measured in [MJ/L PPO] or [kg CO_2 eq/L PPO] depending on whether $EF_{Diesel\ FE}$ or $EF_{Diesel\ GWP}$ is used,$D_{Tractor}$ is the diesel consumed by a tractor doing field work in L/h,$t_{Terrace}$ is the time it takes to make terraces on one ha and $CF_{Ha\ (once)\ to\ l\ PPO}$ converts the unit from [impact/(ha once during the lifecycle)] into [impact/L PPO].

3.2.2 Nursery

The bushes planted in late 2007 and 2008 have all been planted using cuttings. The procedure is simple; a branch from an old bush is cut and planted in the soil. No other input than labor is required. This method was chosen by the farmer at Luambala, despite the fact that cuttings usually produce a lower yield (Heller, 1996, Achten et al., 2008).

From 2011, all bushes planted on new land will be seedlings as this provides a higher potential seed yield. This means that a nursery will be needed where the seeds are propagated for a few months before they are planted in the fields at the start of the rainy season in October or November. The ambition is to cultivate 450 000 seedlings, which will be more than enough to expand the plantation to 450 ha. At the nursery, the jatropha seeds are planted in plastic bags in a mixture of soil from the surrounding forest and seed cake. The seed cake is transported by tractor from the oil press. The impacts stemming from this transport is calculated with equation 3.10.

$$I_{Seedcaketrsp} = EF_{Tractortrsp} \times d_{Press-nur} \times m_{Seedcakenur} \times CF_{Ha\ (once)\ toLPPO} \quad (3.10)$$

Where $d_{Press-nur}$ is the distance traveled in km and $m_{Seed\ cake\ nur}$ is the mass of the transported seed cake in [tons/ha], which is calculated by

$$m_{Seedcakenur} = N_{Plantsperha} \times \frac{V_{Bag}}{2} \times \rho_{Seedcake} \quad (3.11)$$

Because the seedlings are propagated during the dry season, irrigation is required. Irrigation is by a diesel powered pump and the water is taken from the Luambala River. Because the nursery was not established during the field study, the amount of irrigation water required is calculated using the computer program CROPWAT, developed by FAO. These calculations are described in section

3.2.5.When the irrigation requirement $W_{Irrigation}$ [L/ha] is acquired, the fuel requirement for the water pump is calculated byequation 3.12.

$$I_{Pump} = W_{Irrigation} \times \frac{D_{Pump}}{F_{Pump}} \times EF_{Diesel} \times CF_{Ha\,(once)\,toLPPO} \quad (3.12)$$

WhereD_{Pump} and F_{Pump} are the pumps diesel consumption [L diesel/h] and capacity [L water/h] respectively.

3.2.3 Planting

The seedlings are planted manually after being transported the short distance to the plantation by tractor. Equations regarding this transport are similar for those of seed cake transport.

$$m_{Seedling} = N_{Plantsperha} \times V_{Bag} \times \rho_{Soil} \quad (3.13)$$

whichis inserted into equation 3.14.

$$I_{Seedlingtrsp} = EF_{Tractortrsp} \times d_{Nur-plant} \times m_{Seedling} \times CF_{Ha\,(once)\,toLPPO} \quad (3.14)$$

This assumes that that the weight of the seedlings and the filled plastic bags is equal to the weight of just the soil. This is probably a close enough approximation, as the seedling will be small compared to the filled plastic bag.

3.2.4 LCI summary of plantation preparation

The results for the fossil energy use and the global warming potential for the plantation preparation step are summarized in table 3.5.

Table 3.5.LCI summary of FEU and GWP for this step.

Activity	Fossil energy use [MJ/L PPO]	Global warming potential [kg CO2 eq/LPPO]
Terrace	0.0262	0.0018
Water pump	0.0007	0.0000
Transport seedlings	0.0036	0.0002
Transport seed cake	0.0031	0.0002
Total	0.0336	0.0023

3.2.5 Water use calculations of the plantation preparation

The only irrigation water the jatropha plant needs will be applied during the initial stage in the nursery. The water will be pumped from the nearby Luambala River to be used in the jatropha nursery. When modeling the irrigation use in the nursery, the program CROPWAT 8.0 has been used. The input data have been found in literature and modified and are presented in the appendix. The climate data are imported from CLIMWAT 2.0 for the weather station Lichingawhich is located at longitude 35.25E and latitude 13.28S with an altitude of 1365 m. CLIMWAT 2.0 provides information about effective rainfall and the crop water requirements are provided by CROPWAT 8.0. Lichinga is the closest weather station to Luambala, which is slightly hotter, but this data was considered good enough for an approximation since no weather station is located in Luambala.

The planting date of the seeds in the nursery is approximated to be in August and the plantation of seedlings in October to Novemberaccording to the farmer at Luambala. The irrigation requirements in the nursery are obtained from CROPWAT 8.0 with data input according to table A1 in Appendix and with the rain data for Lichinga provided by the program CLIMWAT 2.0. The rain data are presented in table A4 in Appendix.

CROPWAT calculates the crop evapotranspiration losses (ET_c) based on the climate data provided by CLIMWAT and the evapotranspiration data for a reference crop. Since the system is balanced, the evapotranspiration losses of the crop (ET_c) is equal to the crop water requirement (CWR_c) which is also equal to the crop water use (CWU_c) according to equation 3.15.

$$ET_C = CWR_c = CWU_c \quad (3.15)$$

In the study by Gerbens-Leenes and colleagues, the CWU was assumed to be equal to the CWR at all times. That resulted in an overestimation of the CWU when the water available (effective rainfall) was actually lesser than the CWR (Gerbens-Leenes et al., 2009). In this study, the CWU has been estimated to be equal to the CWR when the effective rainfall (R_{eff}) has been larger or equal to the CWR, that is:

$$CWU_c = ET_c \text{when} ET_c \leq R_{eff} \quad (3.16)$$

In case of drought, when the effective rainfall is lesser than the CWR, only the water available, the effective rainfall, has been used by the crop, that is:

$$CWU_c = R_{eff} \text{when} ET_c > R_{eff} \quad (3.17)$$

For the nursery it is assumed that the amounts of irrigation water applied will equal the CWR to be as optimal as possible, which is an underestimation. According to the farmer employed by Chikweti, a roof on the nursery will be used which result in no use of rain water. Hence, for calculating the irrigation water need during the period when the plant is in the nursery, equation 3.16 is used.

When transports or electric generators have been used in the system, the water used to produce the fossil diesel used, must be accounted. Water is often used for cooling in refineries or pumped into the earth's crust to enhance oil recovery. According to a study made by King and Webber (2008), 1-2.5 liters of water per liter produced diesel is consumed. The worst case scenario has been chosen so the factor 2.5 L water/L diesel has been used.

The results from the calculations using CROPWAT, CLIMWAT and the results from the fossil diesel use have been used to calculate the indicators chosen; the *water footprint* and the *actual water resource use*. The calculations are presented below.

3.2.6 Water footprint of the platation preparation

No activities in the nursery use any green water considering that a roof will probably be installed over the nursery area as the farmer notified. The calculation of the blue WF (WF_{Blue})for the plantation preparation step includes the following activities:

$$WF_{Blue} = W_{Irrigation,Blue} + W_{Diesel,plant,prep} + W_{PPO,Blue} \quad (3.18)$$

where every factor is in [m^3/L PPO] and includes the blue water used for irrigation, the water used to produce the diesel consumed in this step and the amount of irrigation water that will finally end up in the finished product, the PPO.

The water use related to diesel consumption is assumed to be only blue water since green water is normally only significant for crops and is calculated according to the factor ($F_{w,Diesel}$)2.5 L water/L diesel produced (King and Webber, 2008). The number is modified according to the total diesel consumption in the system according to equation 3.19.

$$W_{Diesel,plant,prep} = \frac{U_{Diesel,plant,prep}}{EF_{DieselFEU}} \times F_{W,Diesel} \quad (3.19)$$

The $W_{Diesel,plant,prep}$ is in [m^3/L PPO] and $U_{Diesel,plant,prep}$ is the amount of fossil diesel used in this step [MJ/L PPO] and the factor $F_{W,Diesel}$ is the amount of water used to produce diesel [L water/L Diesel].

The blue water use includes uses of water from the Luambala River for irrigation and from surface water used during the production of fossil diesel. The irrigation water use has been calculated using CROPWAT 8.0 with the assumption that the irrigation equals the CWU according to equation 3.16and equation 3.20.

$$W_{Irrigation} = ET_{c,Blue} \times CF_{Ha(once)toLPPO} \quad (3.20)$$

Where $W_{Irrigation}$ [m^3/L PPO] equals the blue water evaporation losses for the crop, $ET_{c,Blue}$ in [m^3/ha] multiplied with the conversion factor $CF_{Ha\ (once)\ to\ L\ PPO}$[ha/L PPO].

The $ET_{c,Blue}$is calculated with equation 3.21.

$$ET_{c,Blue} = A_{Nursery} \times \frac{Jatrophaplants}{ha} \times ET_c \quad (3.21)$$

The $A_{Nursery}$ is the nursery area per plant [dm^2/plant] and the ET_C is the crop evapotranspiration provided by CROPWAT 8.0 [dm].

The water incorporated in the product has been calculated with information about the fraction of water in PPO ($F_{W,PPO}$), which is equal to 0.05 percent according to a product sheet by Alfa Laval (n.d.). When summarizing the total amount of water used by the jatropha tree during its lifetime, the amount of irrigation water (blue water) used (F_{Blue}) represents a fraction of the total water use. Considering the final product, the PPO, the water incorporated represents the same fraction of used blue and green water during the tree's lifetime. The blue water contribution to the water content in PPO is calculated with equation 3.21:

$$W_{PPO,Blue} = F_{W,PPO} \times F_{Blue} \quad (3.22)$$

where the $W_{PPO,Blue}$ is the amount of blue water incorporated in the product [m^3/L PPO], the $F_{W,PPO}$ is in [L water/ L PPO] and F_{Blue} is in [L blue water/ L total water applied].The results from the calculations of blue WF, which in this step equals the total WF since there is no use of green water, are presented in table 3.6.

Table 3.6. The blue WF for the plantation preparation step.

Blue WF for plantation preparation [m3/L PPO]	
Irrigation, $W_{Irrigation}$	0.0004
Diesel consumption, $W_{Diesel,plant,prep}$	2.4E-06
Water incorporated in PPO, W_{PPO}	2.E-11
Total WF	0.0004

3.2.7 Local hydrological cycle deviation of the plantation preparation

The sub-indicators developed for this study; the flow water use, the fund water use and the deposit water use have been calculated and the principles presented in equation3.16has been used to calculate the CWU_c in the plantation preparation step due to the assumption that the irrigation will equal the CWR_c. The indicators have been calculated as the volume of water used per volume of produced PPO [m^3/L PPO]. According to the definition, only the actual consumption of water has been considered in the calculations. In Luambala, the processing site is located only 3 km from the plantations. The Luambala River, where the irrigation water is taken from, is nearby and the local hydrological cycle is assumed to be slightly affected when the water is withdrawn to be used in the nursery, since this is done during the dry season. The use of water from the Luambala River thus belongs to the fund water use. The water incorporated in the PPO is calculated with the same principle as described in the calculations of the water footprint of this step. Since no deposit water or flow water is used during this step, only fund water use (which equals blue water use) has been calculated including fund water incorporated in the PPO and the fund water used to produce fossil diesel used in this step according to equation 3.23:

$$\mathrm{LHCD} = W_{Fu} = W_{P,Fu} + W_{Eq,Fu} = W_{PPO,Blue} + W_{Diesel,plant,prep} \quad (3.23)$$

where all factors are in [m^3/L PPO]. The water used to produce fossil diesel, $W_{Diesel,plant,prep}$ can be calculated with equation 3.19 and the fund water (blue water) that is incorporated in the product $W_{PPO,Blue}$ can be calculated with equation 3.22. Recalling equation 2.8, the $W_{Res,Fu}$ and the $W_{Evap.\ Fu}$ in equation 3.23 are neglected due to that the production site is very close to the plantations and thus belongs to the same hydrological cycle.The results of the calculations are presented in table 3.7.

Table 3.7.The local hydrological cycle deviation for the plantation preparation step.

LHCD for plantation preparation [m3/L PPO]			
Indicator	Incorporated in product	Diesel consumption	Total
Fund water use, W_{Fu}	6.9E-11	2.4E-06	2.4E-06

3.3 Plantation

Every other year, the jatropha bushes are pruned. Each cut branch gives 5-10 new branches, which is believed to increase the fruit yield. By pruning, the harvest is displaced two months ahead, lowering the need for personnel during peak season. The branches are left on the ground for soil improvement. However, when inspecting the field two months after pruning, no branches where found. Theft for firewood use is suspected.

Six years after planting, the planted rows will be thinned by removing every other bush, leaving a grid of 2 x 4 meters between the plants. This should leave enough space for the plants to grow and a tractor to drive down the lanes.

3.3.1 Organic fertilization

For the 208 ha which is currently being utilized,no irrigation or synthetic fertilizers are used. The fruit husks from previous harvests have been applied to other crops as soil improvement. In the future, these, as well as the seed cake, are planned to be spread on the fields to increase the amount of soil organic matter and to return much of the nutrients lost in the harvest. Especially the seed cake contains many nutrients which are lost in the harvest and should be returned to the fields (Achten et al., 2008).

The impacts from the transports used in this step, are calculated in the same fashion as during the plantation preparation but with a different conversion factorusing equation 3.24.

$$I_{OFtrsp} = EF_{Tractortrsp} \times d_{Press-plant} \times (m_{Husk} + m_{Seedcake}) \times CF_{HatolPPO} \qquad (3.24)$$

The amount of husk [tons/ha] that is returned to the fields is of course related to how much is harvested, the average yield [tons dry seed/ha]

$$m_{Husk} = Y \times \frac{Huskperfruit}{Dryseedperfruit} \qquad (3.25)$$

The amount of seed cake returned to the field is calculated in the same fashion using equation 3.26:

$$m_{Seedcake} = Y \times \left(1 - RF \times (Oilcontent + \ Watercontent)\right) \qquad (3.26)$$

where*RF* is the oil recovery factor of the oil press, which is assumed to also affect the amount of water pressed out of the seeds. Apart from husk and seed cake, no other fertilizers are assumed to be required.

3.3.2 Herbicides and pesticides

In Luambala and at the fields managed by Chikweti, weeds are controlled manually or with the herbicide Round-Up (Glyphosate). As the bushes grow, these will hopefully shade the ground enough to prevent many weeds. Removing weeds also has the purpose of preventing fires. By manual weed removal using a hoe, there are no dry weeds to spread the fire. Unfortunately, this also means removing the topsoil which may affect the jatropha. Chemical weeding, one the other hand, is done by a tractor driving down the lanes spraying. Since jatropha is resilient to glyphosate, the herbicide can be applied directly under the bushes. This is less labor-intensive and may be beneficial for the jatropha because of increased soil fertility.However, the dry biomass under the bushes also makes it more susceptible to grass fires.

There are some pest problems, the worst being leaf beetles which eats the leaves. The insects emerge if there is a pause in the rainy season. If there is not sufficient rain to flush away the insects, the affected fields are sprayed with Cypermethrin from a tractor.

Fossil energy is required to drive the tractors and to produce the chemicals. To calculate the FEU and GWP for the tractors,equation 3.27is used for the pesticide and herbicide applications.

$$I_{Spray} = A_{Spray} \times D_{Tractor} \times t_{Spray} \times EF_{Diesel} \times CF_{HatolPPO} \quad (3.27)$$

The factor A_{Spray} is the fraction of the plantation which is sprayed annually, about twenty percent. $D_{Tractor}$ is the diesel consumed by a tractor doing field work in l/h andt_{Spray} is the time required to spray one ha.Values regarding the production of the two chemicals are taken from literature sources (Prueksakorn and Gheewala, 2008, Bernesson, 2004) and the impacts are calculated as equation 3.28. The chemical use and its EFs are presented in table 3.8.

$$I_{Chemicalprod} = A_{Spray} \times m_{Chemical} \times EF_{Chemical} \times CF_{HatolPPO} \quad (3.28)$$

The factor $m_{Chemical}$ is the amount of the chemical applied in [g/ha] and $EF_{Chemical}$is the production impact.

Table 3.8. The amount of applied chemicals and dilution water. The emission factors are cradle-to-gate.

Pesticides	$m_{Chemical}$ [g/ha]	Water [L/ha]	$EF_{Chemical\ FEU}$[MJ/g]	$EF_{Chemical\ GWP}$ [g CO2/g]
Glyphosate	12.5	400	0.4525 (Prueksakorn and Gheewala, 2008)	4.921 (Bernesson, 2004)
Cypermethrin	1080	400	0.1981 (Bernesson, 2004)	4.921 (Bernesson, 2004)

3.3.3 Harvest

The harvest season is between February and May, when fruits mature continuously. Allegedly because of the long harvesting period and the irregularity of the fruits maturation, it is difficult and labor intensive to pick only the yellow fruits. At the Luambala plantation, most of the fruits picked have already become brown and moist because of the heavy rains. This requires additional drying later and might affect the oil yield and quality. Brown fruits also lower the efficiency of the cracking machine later.

The fruits are picked by hand and transported to the cracking machine by tractor. The impacts GWP and FEU associated with this step are calculated with equation 3.29.

$$I_{Harvesttrsp} = EF_{Tractortrsp} \times d_{Plant-crack} \times m_{Harvest} \times CF_{HatolPPO} \quad (3.29)$$

Where$EF_{Tractortrsp}$ is the impact per t km,$d_{Plant-crack}$ is the distance of the tractor transport and $m_{Harvest}$ is the mass of fruits transported, calculated as

$$m_{Harvest} = \frac{Y}{Dryseedperfruit} \quad (3.30)$$

As the yield *Y* is measured in t dry seed/ha and the whole fruit is transported in this step, *Y* is divided by the ratio *Dry seed per fruit* which is roughly 0.25.

3.3.4 Soil emissions

When nitrogen in any form is added to a managed soil, some of it will be converted to N_2O, a strong greenhouse gas. This is due to the processes nitrification and denitrification, where N_2O is an intermediate, produced by natural bacteria. The gas is formed both by direct and indirect mechanisms. The direct mechanism is the conversion in the fields.The indirect N_2O-emissions aredue to the fact that some N will volatilize, leach or runoff in the form of ammonia or nitrate and later be converted to N_2O by bacteria elsewhere.

The emissions vary considerably between different fields, correlated to meteorological, crop and soil factors. The result of all these factors is very difficult to predict for any given plantation. Therefore, IPCC (2007) has developed default emission factors related to the amount of N applied which is often used for approximations of the direct and indirect emissions of N_2O.

Equations from IPCC (2007) are used to calculate the direct and indirect emissions of N_2O. In this study, all nitrogen added is assumed to come from the seed cake application. The seed cake is very nutrient-rich in contrast to the husk (Achten et al., 2008) and very little other crop residue is returned to the fields. Therefore, using IPCC's terminology, the equations comes down to

$$N_2O - N = F_{ON} \times \left(EF_1 + Frac_{GASM} \times EF_4 + Frac_{LEACH(H)} \times EF_5\right) \qquad (3.31)$$

The meaning of the abbreviations and the variables default values is presented in table 3.9.

Table 3.9. Explanation of the variables in equation 3.31, all adapted from IPCC (2007). Leaching and runoff does not occur everywhere, but is assumed to occur at Luambala because of the heavy rains.

Variable or factor	Explanation	Default value
$\mathbf{N_2O - N}$	Total kg of N as N_2O per ha emitted from the managed soil	
$\mathbf{F_{ON}}$	The total kg of N added to the managed soil in manure, compost etc. In this case as seed cake.	
$\mathbf{EF_1}$	Emission factor for N_2O emissions from N inputs	0.01
$\mathbf{Frac_{GASM}}$	Fraction of applied organic N fertiliser materials that volatilises as NH_3 and NO_x	0.2
$\mathbf{EF_4}$	Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces	0.01
$\mathbf{Frac_{LEACH(H)}}$	Fraction of all N added to managed soils that is lost through leaching and runoff	0.3
$\mathbf{EF_5}$	Emission factor for N_2O emissions from N leaching and runoff	0.0075

For the Luambala case, where the added nitrogen comes from the seed cake, which has a nitrogen content of 3.5 percent (Achten et al., 2008), the parameter $F_{ON}$is calculated as

$$F_{ON} = m_{seedcake} \times 0.035 \qquad (3.32)$$

When the N_2O emissions are known, the GWP can be calculated with equation 3.33.

$$I_{Soil} = N_2O - N \times \frac{44}{28} \times ChF_{N2O} \times CF_{HatolPPO} \qquad (3.33)$$

Where the characterization factor ChF_{N2O} is the relative heat absorption of N_2O, that is 298 kg CO_2 eq / kg N_2O (IPCC, 2007).

3.3.5 LCI summary of plantation

The fossil energy use and the global warming potential for the plantation step aresummarized in table 3.10.

Table 3.10. Summarize of the FUE and GWP for the plantation step.

Activity	Fossil energy use [MJ/L PPO]	Global warming potential [kg CO2 eq/L PPO]
Pesticide spraying	0.16	0.011
Pesticide production	0.16	0.004
Herbicide spraying	0.39	0.027
Herbicide production	0.01	0.000
Transport harvest	0.59	0.040
Transport husk	0.33	0.022
Transport seed cake	0.11	0.007
Soil emission	-	0.697
Total	1.74	0.81

3.3.6 Water use calculations of the plantation

When the plants in the nursery have reached the developing stage, the jatropha plants are planted in the fields. No irrigation will be used during this step or during the rest of jatropha's lifetime. The only water consumed by the plant will be rainwater and this is calculated with equation 3.16 and 3.17 depending on the rainfall. The first harvest can be achieved 6-12 months after planting the seed in the nursery (Heller, 1996) and thus the first harvest will be in February to May the following year. The jatropha plant's first year is divided into differenttime periods to simplify the water calculations and the parameters used in the program CROPWAT 8.0 for the first year can be found in table A1 and A2 in Appendix. The expected lifetime of a jatropha plant is 30 years, as discussed earlier, andhence this number is used in the calculations. The parameters for the plant from year 2-30 are presented in table A3 in Appendix.

3.3.6.1 Water footprint of the plantation

In the plantation there is use of both blue water and green water and the total WF can be calculated with equation 3.34.

$$WF_T = WF_{Blue} + WF_{Green} \qquad (3.34)$$

All factors are in [m^3/L PPO]. No irrigation is used in the plantations and the use of blue water in this step equals the water taken from the Luambala River to dilutethe chemicals and the water used to produce the diesel consumed in this step. The blue WF (WF_{Blue}) for this step can be calculated with equation 3.35.

$$WF_{Blue} = W_{Dilution} + W_{Diesel,plant} \qquad (3.35)$$

where $W_{Dilution}$is the water used to dilute the chemicals used on the field [m^3/L PPO] and the $W_{Diesel,plant}$ is the water used to produce the fossil diesel used in the plantation step [m^3/L PPO].The dilution of chemicals ($W_{Dilution}$)used on the fields has been calculated regarding to data on concentrations of the chemicals used at Luambala according to the farmer. It can be calculated with equation 3.36.

$$W_{Dilution} = (W_{Glyphosate} + W_{Cypermethrin}) \times CF_{HatoLPPO} \quad (3.36)$$

The $W_{Glyphosate}$ is the water amounts used to dilute glyphosate [L/ ha] and respectively the $W_{Cypermethrin}$is the water used for dilution of cypermethrin [L/ha]. The $CF_{Ha\ to\ L\ PPO}$is the conversion factor per 30 years due to yearly activities.

As mentioned above, the water use related to diesel consumption is assumed to be only blue water as in the plantation preparation step. The same principle applies for the water incorporated in the product. To calculate $W_{Diesel,plant}$, the equation 3.19 can be used, changing the factor $U_{Diesel,plant,prep}$ to $U_{Diesel,plant}$.

The green water includes the crop water use which equals the evapotranspiration and effective rainfall (rainwater available for the crop) that has been calculated using the principle described above using equations 3.16 and 3.17, resulting in a green crop water use (CWU_{Green}). The green WF for the plantation step can be calculated with equation 3.37.

$$WF_{Green} = CWU_{Green} + W_{PPO,Green} \quad (3.37)$$

All factors are in [m^3/L PPO]. The $W_{PPO,Green}$ is the green water fraction of the water incorporated in PPO and can be calculated with equation 3.22 using the F_{Green} instead of F_{Blue}. The green crop water use, CWU_{Green}can be calculated with equation 3.38.

$$CWU_{Green} = ET_{c,Green} \times CF_{HatoLPPO} \quad (3.38)$$

The $ET_{C,Green}$ is the green fraction of the crop evaporation [L/ha] and $CF_{Ha\ to\ L\ PPO}$is the conversion factor for 30 years. The results of the blue- and the green WF are presented in table 3.11.

Table 3.11. The blue water footprint and the green water footprint of the plantation step.

Water footprint of plantation [m3/L PPO]			
Blue WF		**Green WF**	
Dilution of chemicals on fields, $W_{Dilution}$	0.0006	CWU_{Green}	23.48
Diesel consumption, $W_{Diesel,plant}$	0.0001	Water incorporated in PPO, W_{PPO}	4.9E-07
Total	0.0007	Total	23.48

3.3.6.2 Local hydrological cycle deviation of the plantation

The evaporated water from the fruits and seeds and water retained in the oil pressing are considered to belong to the same hydrological system as the plantation and these water uses are neglected (W_{Evap} and W_{Res} are equal to zero). The only water removed from the system is the water content in the finished jatropha oil and since no deposit water is used the LHCD can be calculated with equation 3.39.

$$LHCD = W_{Fl} + W_{Fu} \quad (3.39)$$

The local hydrological cycle deviation,*LHCD* in [m^3/L PPO] thus only includes the uses of flow water and fund water in this step. The fund water use, W_{Fu}, only includes the water used to produce the diesel used in this step, since it is assumed that fund water is used in the production of fossil diesel. Libya utilizes much deposit water from aquifers in the southern parts of the country. The assumption that fund water is used here is based on that the fossil diesel is produced in near the coast. The fund water use is calculated withequation 3.40.

$$W_{Fu} = W_{Eq,Fu} = W_{Diesel,plant} \quad (3.40)$$

All factors are in [m^3/L PPO] and the water used to produce diesel, $W_{Diesel,\ plant}$, can be calculated in the same way as for the blue water footprint using equation 3.19.

The reason not to include the water used for dilution of chemicals in these calculations is because it is assumed that the water used is taken from the Luambala river. When this water is evaporated on the field it is according to the definition assumed to belong to the same local hydrological system as the Luambala river.

Since the jatropha tree belongs to the local system, the evapotranspiration losses associated to the tree are neglected. The flow water usecan be calculated with equation 3.41 only including the amount of flow water incorporated in the product as according to the definition.

$$W_{Fl} = W_{P,Fl} = W_{PPO,Green} \quad (3.41)$$

Where the $W_{PPO,Green}$ [m^3/ L PPO] can be calculated in the same way as for the water footprint using equation 3.22. The results are presented in table 3.12.

Table 3.12 Thelocal hydrological cycle deviation divided into flow water use and fund water use.

LHCD for plantation [m3/L PPO]			
Indicator	Incorporated in product	Diesel production	Total
Flow water use	4.9E-07	0	4.9E-07
Fund water use	0	0.00012	0.00012
Total water use	4.9E-07	0.00012	0.00012

3.4 Oil processing

After the agricultural stage it is time to process the harvested jatropha into jatropha pure plant oil (PPO) which can be used directly in some compression ignition engines, as a blend in diesel or further processed into biodiesel. At the time of the field study, drying and cracking was subjected to some experiments, but no standard procedure was yet developed. Regarding the functionality of the oil press, the uncertainty is even larger. The processes described below are therefore predictions much based on literature and trends at Luambala.

3.4.1 Drying and cracking of fruits and seeds

The ripe yellow fruits sometimes have to be dried before they can be processed by a cracking machine. The brownfruits can be very moist after rains and always has to be dried before processing. The drying is done by letting the fruits lie on large plastic sheets in the sun. The duration is a few days, depending on the weather.

After drying, it is time for the fruits to be cracked open and the seeds removed. This can be done manually or with a cracking machine. Such machines come in many sizes and can be driven by hand or with an engine. The principle lies on provocation of a slight pressure and friction which makes the husk crack and separate from the seeds. The friction is created by a horizontal rotating cylinder of mesh, se figure 3.3.

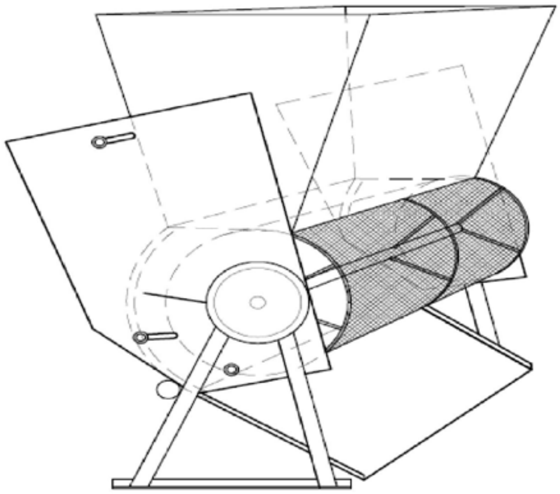

Figure 3.3.A picture of a mechanical cracker which is used to make the fruits crack open.(Galema, 2010).

At Luambala, cracking is done by one of two cracking machines. One machine is for the ripe yellow fruits, but since many fruits are harvested after turning brown another more suitable machine is used for these. The need for this is due to the different characteristics of the fruits, since the yellow fruits are bigger and harder. Both machines work by mechanically cracking the nuts open and separating the seed from the husk in a rotating drum with small enough holes for the seeds to fall out of. Both machines can be powered by a tractor but the cracker for the yellow fruits will be equipped with an electric motor in the near future.

For calculation purposes, the two machines are assumed to work at similar speed and input processing the same amount of fruits, both being powered by a tractor. The impacts in this step can be calculated with equation 3.42.

$$I_{Cracker} = \frac{D_{Cracker}}{F_{Cracker}} \times EF_{Diesel} \times CF_{kgdryseedtolPPO} \quad (3.42)$$

In equation 3.42 the factor$D_{Cracker}$ is the hourly diesel consumption of the John Deere tractor powering the cracker. $F_{Cracker}$ is the machines capacity in [kg dry seed/h].

The machines fail to sort out all husks and these are sorted out manually from the seeds. A disadvantage with harvesting brown fruits is that these are cracked less efficiently; resulting in approximately ten percent of the fruits passes intact through the machine, ending up with the husks. Too manually sort out non-cracked fruits from the husk is difficult and is not done in Luambala.

The husks are put on a compost to be used as soil improvement, whereas the seeds are being dried once more before being stored in textile bags awaiting pressing. Aeration is important to preserve the seeds, which is done by using appropriate bags and storing them in a space with no walls and a roof. How long the seeds can be stored depends on if the seeds are to be used for plantation or only oil production. The seeds should not be stored longer than 8 months because that affects the oil quality negatively. The dryer the seeds are, the lower is the efficiency of the press, but they can be stored for a longer time if they are dry. It is recommended that the pressed seeds have a moisture content of 7-10 percent and less storing time according to Gilema (2010).

3.4.2 Oil pressing

When the seeds have dried the oil can be extracted. Mechanical extraction methods use a press technique and can be of either ram, hydraulic or screw type. The mechanical methods can be operated by hand or an engine. There are also chemical methods which use organic solvents or water, supercritical extraction or the so-called three-phase partitioning extraction method. Chemical extraction usually has a higher oil recovery factor, but is usually adapted to industrial scale extraction (Beerens and van Eijk, 2010).

The oil press Luambala operates is a cold press screw press denoted KEK-P0500 and is manufactured by KEK Egonkeller GmbH & Co in Germany. Cold in this case means below 60°C, in contrast to hot pressing which operates at temperatures above 100°C. Hot pressing has a higher yield but requires more purification. A screw press presses the oil continuously as the seeds are fed into the feed hopper and then pushed and squeezed by the screw from one side of the press to the other. Near the feeding end, the seeds are loosely fed, but as they are pressed along the nozzle, the air between the voids is slowly pressed out resulting in deforming of the seeds. As more seeds are fed into the press, a higher pressure is formed in the nozzle and the oil in the seeds is pressed out. The pressed oil flows from the bottom of the screw and at the end of the nozzle, the seedcake is formed. See figure 3.4 (Beerens and van Eijk, 2010).

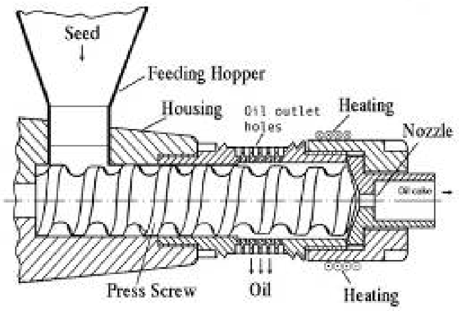

Figure 3.4. Picture of the different parts of the screw press (Beerens and van Eijk, 2010).

The KEK-P0500 is operated by electricity and has a theoretical maximum capacity of 500 kg vegetable oilseeds/h (Keller-Egon Keller Gmbh & Co. KG, 2011). The oil press consumes about 16 kW of electricity at normal pressing speed (Keller,2011). According to experiments performed by FACT Foundation (organization doing research of jatropha oil in Africa) on several oil presses, the capacity of pressing jatropha seeds is 350 kg seeds/h and the oil recovery factor is 80% for this particular model (Beerens and de Jongh, 2008).

To provide the oil press and other appliances at Luambala farm with electricity an Atlas Copco QAS100 diesel generator will be installed. To run the press at maximum speed, the large generator will only have to run run at approximately twenty percent load. The diesel consumption at this load, $D_{Generator\ 20\ \%\ load}$, is calculated by linear interpolation of diesel consumption at zero and fifty percent load (Atlas Copco, 2008). The impact of running the press is then calculated by

$$I_{Press} = \frac{D_{Generator\ 20\ \%\ load}}{F_{Press}} \times EF_{Diesel} \times CF_{kgdryseedtolPPO} \qquad (3.43)$$

whereF_{Press} is 350 kg seeds/h.

The pressed oil contains a lot of water and 5-15 percent solid residues which will be removed by sedimentation in several steps, which is a cheap way to purify the oil. Each step is a batch which naturally separates the oil on the top, oil mixed with water and residue in the middle and water at the bottom because of gravity and different densities. The principle is illustrated in figure 3.5. At Luambala, the sedimentation system is subjected to some experimentation and the definite exact setup is not decided.

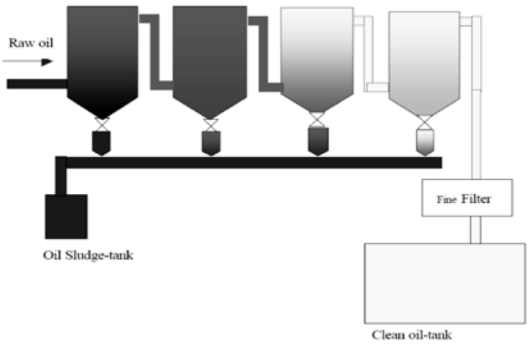

Figure 3.5. The sedimentation principle, using several tanks, used to purify the pressed oil at Luambala (Beerens and van Eijk, 2010).

The seedcake will be used as a fertilizer for the crop plantations and on the jatropha plantations. It is not yet decided how the seedcake will be divided between the fields. Probably this depends on different needs during different periods.

3.4.3 Transport to Lichinga

Chikweti operates from Lichinga, which means the PPO has to be transported there before it can be considered to be ready to use. To transport large amount of PPO on a pickup is not efficient and a medium sized truck is assumed to be used instead. The emissions from this mode of transport ($EF_{Medium\ truck\ trsp}$ in MJ/t km) is acquired from literature sources (NTMcalc, n.d.) and the impact is calculated as

$$I_{Lichingatrsp} = EF_{Mediumtrucktrsp} \times d_{Luambala-Lichinga} \times \frac{\rho_{PPO}}{1000} \qquad (3.44)$$

The factor $\rho_{PPO}$is the density of PPO in [kg/L].

3.4.4 LCI summary of oil processing and transportation

The summarized results of the FUE and the GWP for the oil processing step are presented in table 3.13.

Table 3.13. The summarized results of the oil processing results and transportation.

Activity	Fossil energy use [MJ/L PPO]	Global warming potential [kg CO2 eq/L PPO]
Cracker	7.71	0.52
Oil press	2.96	0.20

Transport to Lichinga	0.20	0.013
Total	12.84	1.56

3.4.5 Water use calculations of the oil processing

The water use in the oil processing step includes the water used to produce the fossil diesel consumed to run the cracking machine, the oil press and the transportation to Lichinga. The only contribution to the WF is the use of blue water and for the actual water resource use, only fund water has been used. They can be calculated using the same equation3.45.

$$W_{Fu} = WF_{Blue} = W_{Diesel,cracker} + W_{Diesel,oilpress} + W_{Diesel,transp} \quad (3.45)$$

Where all have the same unit [m^3/L PPO] and the $W_{Diesel,\ cracker}$, $W_{Diesel,\ oil\ press}$and the$W_{Diesel,\ transp}$can be calculated with equation 3.19, substituting to $U_{Diesel,cracker}$, $U_{Diesel,oil\ press}$and $U_{Diesel,\ transp}$ respectively. The results for the water footprint and the actual water resource use are presented in table 3.14.

Table 3.14. The water footprint and the LHCD for the oil processing step which includes the cracking machine, the oil press and transportation.

Oil processing				
Indicators[m3/L PPO]	Diesel,Cracker	Diesel,Oil press	Diesel, Transports	Total
Blue WF	0.00055	0.0002	1.4E-05	0.0008
Fund water	0.00055	0.0002	1.4E-05	0.0008

3.5 Use

When burning a biofuel the CO_2 emissions are generally regarded as not affecting the climate, because the emitted carbon is not of fossil origin. This notion was established since an OECD report in 1991 and the idea has since then been common practice when performing life cycle inventories and elsewhere. Therefore, no impacts are considered for the use phase in this report.

3.6 Reference system

The calculations for the reference system include calculations for GWP, Fossil energy use and water use. The fossil diesel is assumed to be produced in Libya and the crude oil extraction is assumed to be carried out at the Bouri offshore field. The crude oil is then transported to the refinery. Since the transportation mode used to transport the oil and the distance is unknown, the activities associated with transporting the crude oil are neglected since the Bouri field is assumed to be close to the Brega refinery.

In the refinery the oil is processed into several refinery products (diesel accounts for 13.4% of the total production). The data are taken for an average U.S. refinery presented by the paper of Sheehan and colleagues. The emissions for the diesel production are allocated between the emissions for the gasoline production in their study (Sheehan et al., 1998). The diesel is assumed to be transported by a coastal tanker ship from Tripoli, Libya to Beira, Mozambique and the distance is approximately 9671 km (Portworld, 2011).The diesel is then transported by road with a medium truck from Beria to Lichinga where it will be used. Chikweti is assumed to mostly use cars of the model Toyota Hilux since this model was the most occurring car within the company. The car weights about 1.2 ton without load (carfolio, 2011) with an average fuel consumption of 6.9 L/km (Toyotaworld, 2011).

To calculate the GWP contribution, the CO_2-, CH_4- and the N_2O-emisissions are multiplied with the GWP factors into CO_2-equivalents/L diesel. To calculate the FEU, the fossil energy use is summarized and converted into the unit [MJ/L diesel]. The global warming potential is calculated with equation 3.46.

$$GWP_{T,Fossil} = GWP_{Oilextraction} + GWP_{Refinery} + GWP_{Transports} + GWP_{Use} \qquad (3.46)$$

where every factor is presented in the unit [kg CO_2-eq/L Diesel]. The four contributors are calculated with equations 3.47, 3.48 and 3.49.

$$GWP_{Oilextraction} = \left(\left(CO_2 \times ChF_{CO_2}\right) + \left(CH_4 \times ChF_{CH_4}\right) + \left(N_2O \times ChF_{N_2O}\right)\right) \times$$

$$\times \delta_{Diesel} \times F_{Diesel/Crudeoil} \qquad (3.47)$$

Where the CO_2, CH_4(methane) and N_2O are the amounts of emissions emitted in the oil extraction process according to literature (Sheehan et al.,1998) in [kg/kg crude oil]. The *ChF*-factors are the characterization factors for GWP 100 years presented in table 2.1. Theδ_{Diesel} is the density of diesel, but in this equation it is used as the density for crude oil, assuming they are similar [kg crude oil/ L crude oil]. The $F_{Diesel/Crude\ oil}$ is the fraction of produced diesel per liter crude oil [L diesel/L crude oil].

The $GWP_{Refinery}$ is calculated in the same way as $GWP_{Oil\ extraction}$ (equation 3.47) using the amounts of emissions emitted in the refinery.

The GWP for transportations, $GWP_{Transports}$, is a sum of the GWP for road transportation and GWP for sea transportation. The GWP_{Road} can be calculated with equation 3.48.

$$GWP_{Road} = EF_{MediumtrucktrspGWP} \times \frac{ton}{kg} \times D_{Road} \times \delta_{Diesel} \qquad (3.48)$$

Where GWP_{Road} is the emissions from road transportation [kg CO_2-eq/L Diesel], the $EF_{Medium\ truck\ trsp\ GWP}$ is the emission factor for road transportation in [kg CO_2-eq/tonkm] obtained from literature (NTMCalc, n.d.), the $D_{Road}$is the transportation distance by road and $\delta_{Diesel}$is the density of diesel [kg/L].

The GWP for the sea transportation can be calculated with equation 3.49.

$$GWP_{Sea} = \left(CO_2 \times ChF_{CO_2}\right) + \left(CH_4 \times ChF_{CH_4}\right) \qquad (3.49)$$

The GWP_{Sea} is the GWP contribution from the sea transportation,CO_2 and CH_4 are the amounts of emissions emitted per liter transported diesel from (NTM, 2008) in the unit [kg CO_2-eq/ L transported diesel]. *ChF* is the same GWP factors used in equation 3.47. The GWP_{Use} is obtained from literature (NTMCalc, n.d.).

The calculations of fossil energy use (FEU) are performed using the following equations:

$$FEU_{T,Fossil} = FEU_{Oilextraction} + FEU_{Refinery} + FEU_{Transports} + FEU_{Use} \qquad (3.50)$$

Where all factors are in the unit [MJ/L Diesel]. The $FEU_{Oil\ extraction}$ is calculated with equation 3.51.

$$FEU_{Oilextraction} = PE_{crudeoil,oilext} \times F_{Diesel/Crudeoil} \times \delta_{Diesel} \quad (3.51)$$

Where $PE_{Crude\ oil,oil\ ext}$ is a value found in literature (Sheehan et al.,1998) that denotes the total primary energy used in the oil extraction process [MJ/kg diesel]. The $FEU_{Refinery}$ is calculated in a similar way using equation 3.51 but instead using the total primary energy for the refinery, $PE_{Refinery}$(Sheehan et al., 1998).

The $FEU_{Transports}$ is a summation of the road transportation and the sea transportation and the FEU for the road transportation can be calculated using equation 3.52.

$$FEU_{Road} = EF_{MediumtrucktrspFEU} \text{X} \frac{ton}{kg} \times d_{Road} \times \delta_{Diesel} \quad (3.52)$$

The $EF_{Medium\ truck\ trsp\ FEU}$is the emission factor [MJ/tonkm] from NTMcalc(n.d.), the d_{Road} is the transportation distance [km] and the $\delta_{Diesel}$is the density of diesel [kg/L]. The FEU for the sea transportation can be calculated with equation 3.53.

$$FEU_{Sea} = \frac{Fuel \times d_{Sea}}{CC \times CL} \times E_{Diesel} \times \delta_{Diesel} \quad (3.53)$$

Where *Fuel* is the fuel consumption of the boat [ton fuel/km], d_{Sea} is the distance transported by sea [km].*CC* is the cargo capacity [tonne] and the *CL* is the capacity load [%]. It is assumed that the boat runs on diesel, which is reasonable for calculation purposes.E_{Diesel} is the energy content in fossil diesel [MJ/kg] and the δ_{Diesel} isits density [kg/L].

Since all use of diesel is considered a fossil energy use when consumed, the FEU_{Use} equals the energy content of diesel.

The contributions from the different parts of the reference system are summarized and the results are presented in table 3.15.

Table 3.15. The fossil energy use and the global warming potential for the different activities in the reference system.

Activity	Fossil Energy use [MJ/L diesel]	Global warming potential [kg CO2 eq/ L diesel]
Raw oil extraction	1.02	0.003
Refinery	0.31	0.041
Transportation	2.16	0.148
Use	35.1	2.7
Total	38.6	2.9

The water footprint and the local hydrological cycle deviation (LHCD) have been calculated for the reference system. Since only blue water/fund water is assumed to be used in the production of fossil diesel, the results for the water footprint and the fund water are the same since their definitions of blue water use and fund water use are equal. The fund water used in the reference system is assumed not to be returned to its origin and is assumed to be removed from the local hydrological system, which is why the total amount of consumed water is considered in the calculations. The data for the water use consumption in the processes is obtained from literature and is 2.5 L water/L diesel produced (King and Webber, 2008).

The results from the water use assessment of fossil diesel are summarized in table 3.16.

Table 3.16. The results from the water use assessment of the reference system.

Water use indicator	Reference system
Water footprint [m3/L product]	0.0025
LHCD [m3/L product]	0.0025

4 Impact Assessment

In this chapter, the results of the study are summarized and presented in diagrams and tables for the three impact categories global warming potential, fossil energy use and water use. The calculations are presented in chapter three.

The figures and tables presented below illustrate the impacts stemming from the studied system, see chapter 2.2 and figure 2.1.

4.1 Fossil energy use

The total FEU for the jatropha production system and the fossil reference system is presented in figure 4.1.

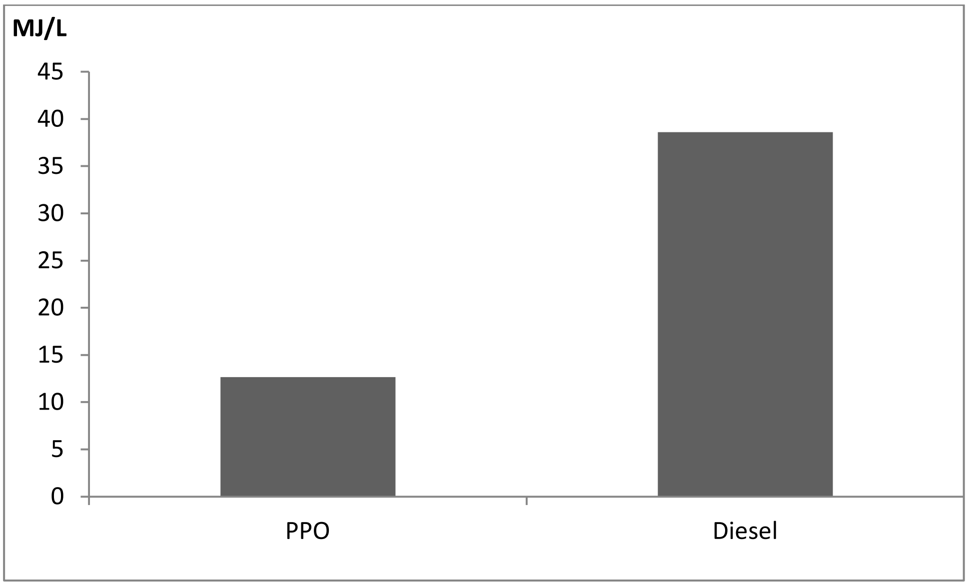

Figure 4.1. The total FEU for PPO and diesel.

The FEU is roughly one third for PPO as it is for fossil diesel. The energy use of producing PPO is mostly due to the use of diesel to power machines, see figure 4.2.

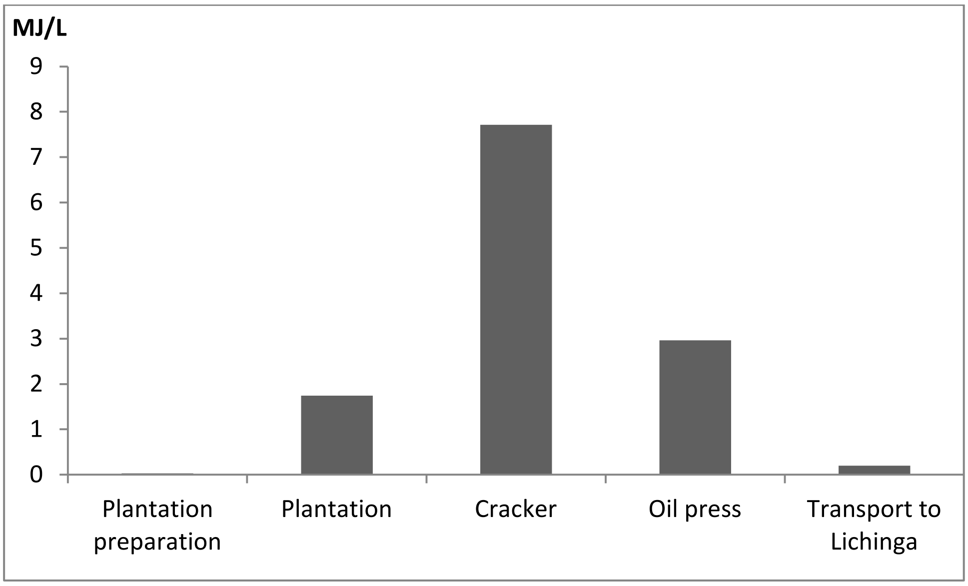

Figure 4.2. The FEU of the different processes for when producing jatropha PPO.

The cracker, powered by a diesel-driven tractor and the oil press, powered by a diesel generator are the two most energy intensive steps. Only third comes the entire plantation phase with different field works and transports. Because of the 30 years lifespan of the jatropha bushes, energy use in the plantation preparation phase contributes very little to the total FEU. Also, the final transportation of the PPO is comparatively quite efficient. As PPO contains no fossil energy, the use phase does not contribute to the FEU at all.

4.2 Global warming potential

The total GWP for the jatropha production system and the fossil reference system is presented in figure 4.3.

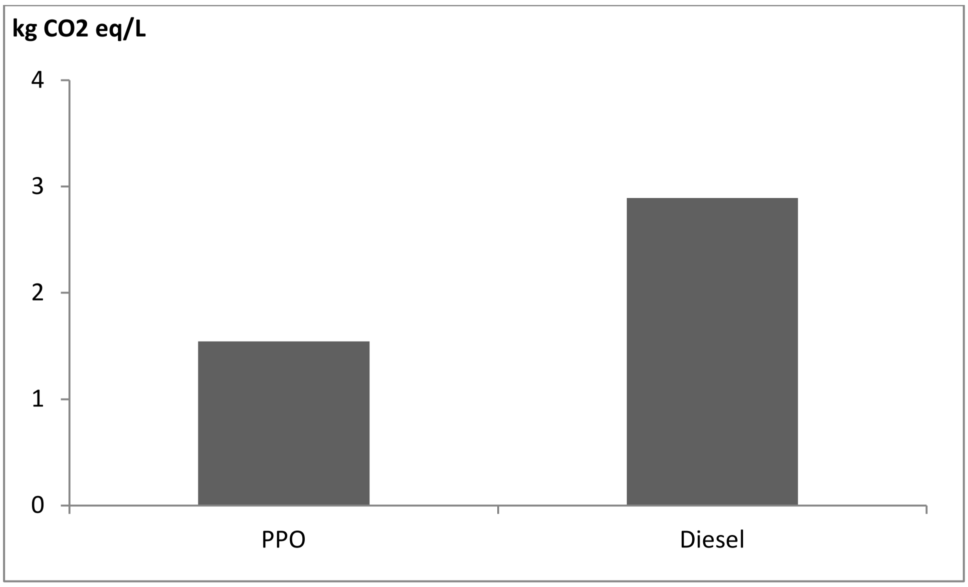

Figure 4.3. The total GWP for PPO and diesel.

PPO from jatropha has about half the impact on the global climate as diesel, per liter. Even though burning of biofuels does not contribute directly to climate change, the life cycle impacts can be considerable. The main reason for this is the emissions of N_2O due to organic fertilizer application and the use of the cracker,see figure 4.4.

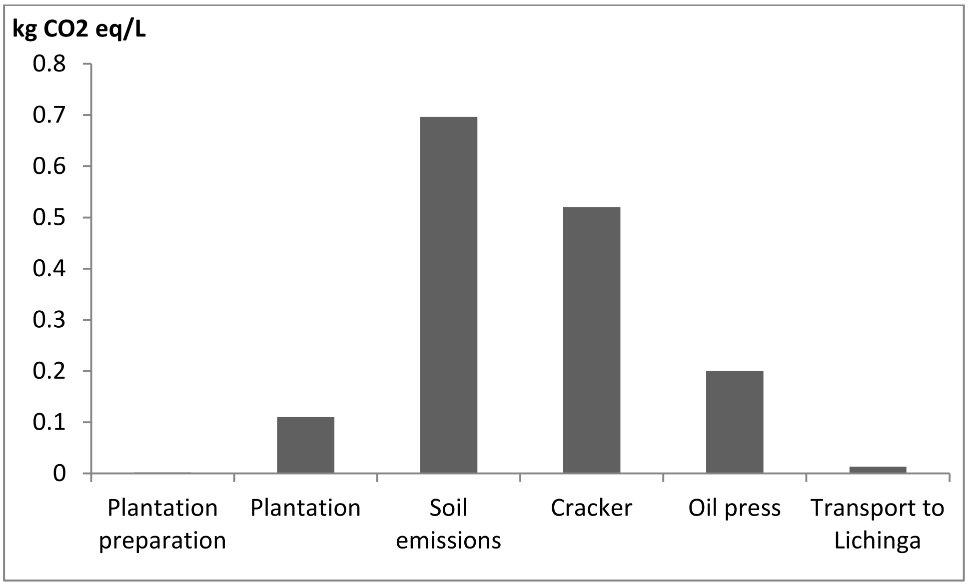

Figure 4.4. The GWP of the different processes and soil emissions for when producing jatropha PPO

Apart from the soil emissions, figure 4.4 is similar to figure 4.2, because most CO_2-emissions are due to the burning of diesel. The soil emissions are the major factor affecting the total GWP despite the fact that no synthetic fertilizer is used. Accounting N_2O is however by nature uncertain and the uncertainty of these calculations is high, see chapter 5.2.

4.3 Water use

The water use indicators used in this study, the water footprint and the local hydrological cycle deviationhas been assessed in the different parts of the study. In this section the partial results have been summarized and the final results are presented in table 4.1.

Results for the water use assessment				
Water Footprint [m3/L PPO]	Plantation prep	Plantation	Oil processing	Total
Green WF	0	23.48	0	23.48
Blue WF	0.00039	0.0007	0.0008	0.0019
Water footprint total	0.00039	23.48	0.0008	23.48
LHCD [m3/L PPO]	Plantation prep	Plantation	Oil processing	Total
Flow water use	0	4.9E-07	0	4.9E-07
Fund water use	2.4E-06	0.00012	0.0008	0.0009
Deposit water use	0	0	0	0
LHCDtotal	2.4E-06	0.00012	0.0008	0.0009

Table 4.1. Summary of the results of the water use indicators used in this study, the water footprint and the local hydrological cycle deviation.

The total water footprint was calculated to be around 23.5 m^3 water/L PPO produced which includes both the green WF and the blue WF. The indicators developed for this study only account for the actual use of water and the final result is 0.0009 m^3/L PPO produced (0.9 L water/ L PPO).

The results obtained from the study of the jatropha production system are compared with the results from the reference system. The comparison is presented in table 4.2.

Table 4.2.A comparison of the results obtained from the water use assessment for the jatropha production system and the reference system.

Indicator	Jatropha production system	Reference system
Water footprint [m3/L product]	23.5	0.0025
LHCD [m3/L product]	0.0009	0.0025

The results show that the water footprint for the jatropha production system is almost a factor of 10 000 larger than for the reference system which only uses blue water in the production. The LHCDfor the jatropha system is almost 30 percentof the reference system since the total amount of fund water used in the reference system is considered as an actual use.

5 Sensitivity analysis

In chapter five the results of the sensitivity analysis are presented and the results are discussed. The parameters analyzed are the yield, soil emissions and fruit characteristics. It also discusses the possibilities of using produced PPO within the system and the consequences of doing so.

To examine the extent ofhow an input parameter affects the final results, it can be varied within its uncertainty range.To check the robustness of the results in this way fashion is called a sensitivity analysis. Some parameters used in the study have been chosen to be examined inthis way,these where the yield, the soil emissions and the fruit characteristics. The reasons to examine the yield is that it can vary a lot according to literature and the yield used in the calculations in this study is based on assumptions. The soil emissions are a large factor contributing to the GWP and are associated with a large uncertainty. The fruit characteristics are examined to see how the management of the harvested fruits affects the results. The result of the analysis is presented in this section and gives an indication of the parameter's impacts on the final results.

5.1 Yield

To see how varying of the yield affects the results, a sensitivity analysis has been performed of the yield parameter. The yield of jatropha seeds per hectare varies in literature as described in section 3.1.1. The yield can vary from 0.4 – 12 ton seeds/ha (Achten et al., 2008), but since 12 ton seeds per hectare is far from being possible in Luambala the two studied alternative yields were chosen to be 0.5 ton and 4 ton seeds/ha, as these values seems plausible for the site specific conditions since a higher yield than 4 ton seeds/ha seems unlikely. These new values were used in the calculations and new results were obtained for the global warming potential, the fossil energy use and the water use assessment that were used in the comparisons with the field study results.

5.1.1 Fossil energy use

The main contributing life cycle phases to the FEU are the cracker and the oil press. The allocation of FEU to these phases is not affected by varying the yield, which results in a robust value for the total FEU. In figure 5.1, the total FEU is seen to vary little.

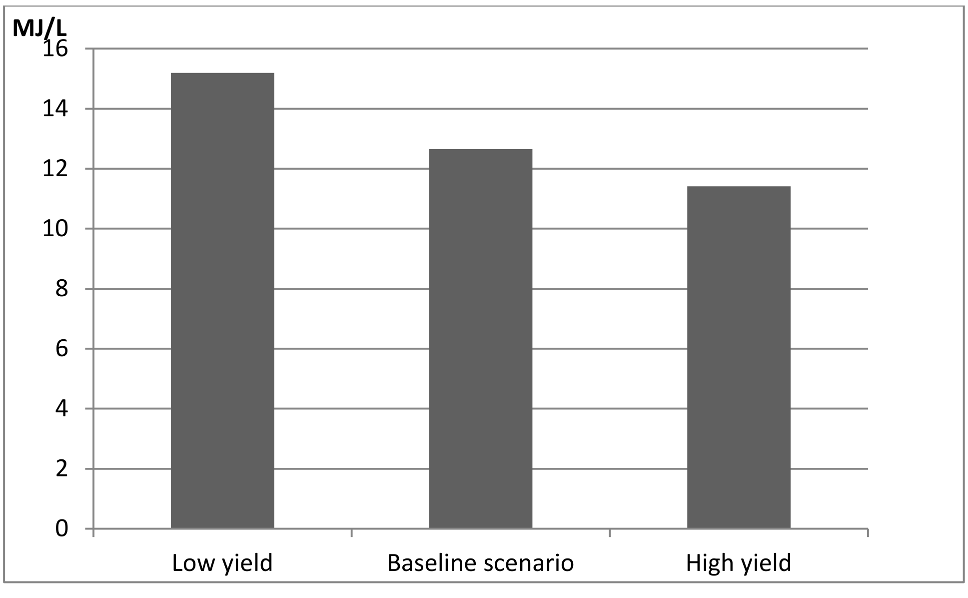

Figure 5.1. The total FEU of producing PPO as it varies with the yield.

5.1.2 Global warming potential

The main contributor to GWP for jatropha cultivation is that of N_2O emissions. These emissions are allocated to the yield, thereby greatly affecting the total GWP as in seen in figure 5.2.

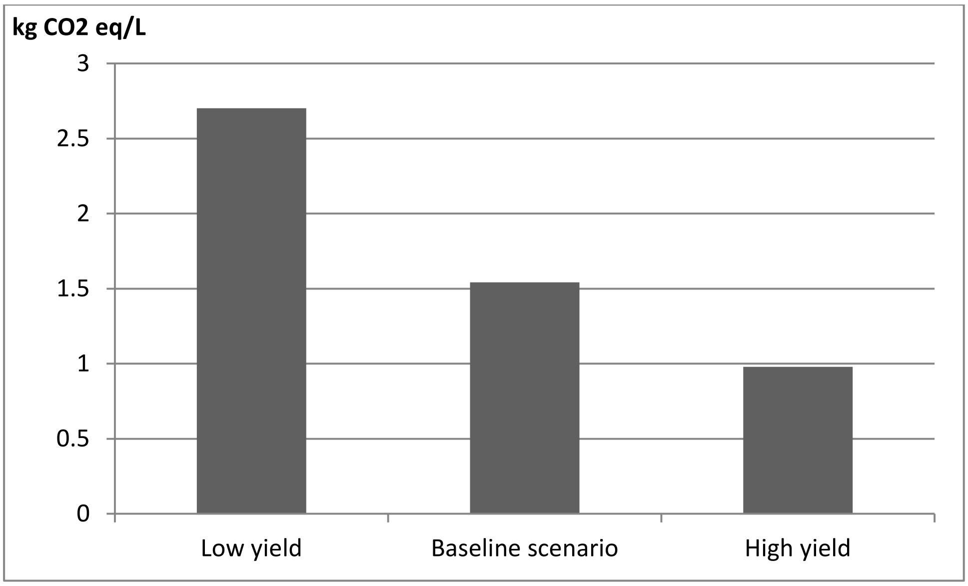

Figure 5.2. The GWP, as it is affected by a change in the yield.

5.1.3 Water use

Varying the yield changes the results for the water use assessment calculations. The results of the changes for the water footprint and the actual water resource use are presented in figures 5.3and 5.4.

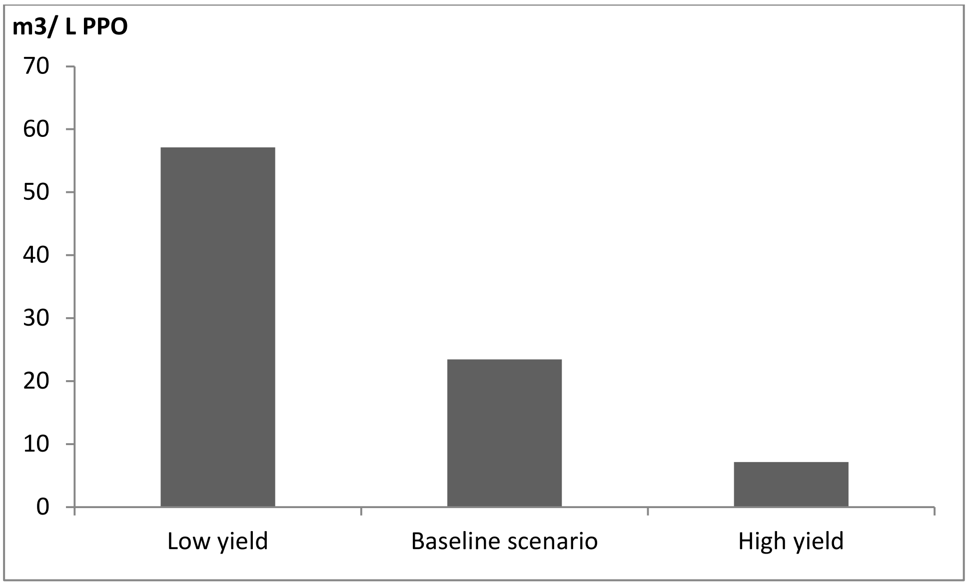

Figure 5.3. The change in result of the water footprint assessment when varying the yield.

The water footprint is highly dependent on the yield and when the yield is reduced to 0.5 ton, the WF is 2.5 times higher. If it is increased to4 ton, the water footprint is more than halved indicating that the yield is highly affecting the water footprint.

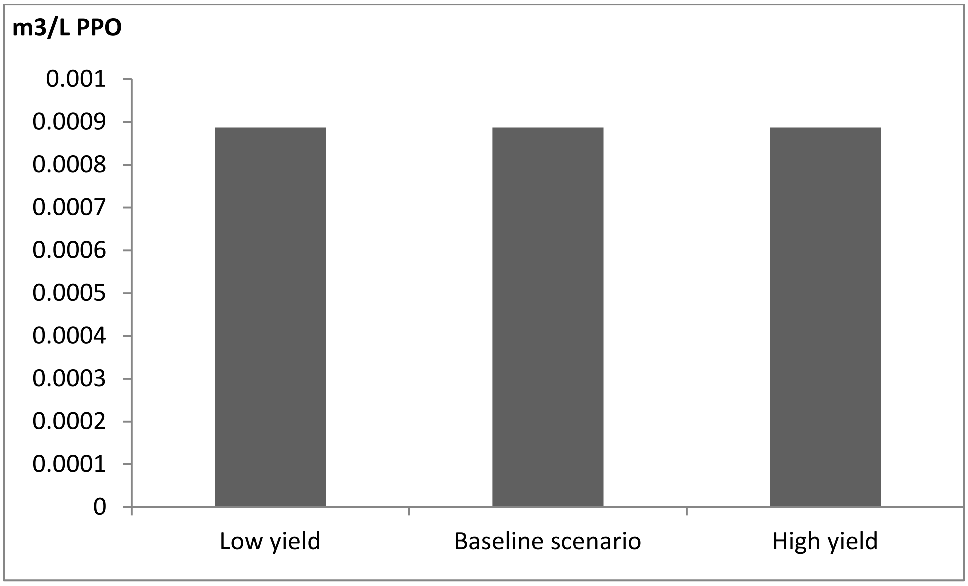

Figure 5.4. Illustration of the change in result for the LHCD when the yield is varied.

Since no factors in the calculations of the local hydrological cycle deviation are dependent on the yield, the change in yield does not correspond to any changes in the results.

5.2 Soil emissions

A large part of the GWP of PPO is due to direct and indirect emissions of N_2O after fertilization using the seed cake, see chapter 4.2. This value is however uncertain for two reasons. The first is that the nitrogen content of the seed cake was not measured, but the used value 3.5 percent was obtained from Heller (1996). Achten et al. (2008) mentions nitrogen content of 1.5 to 4 percent by weight. The emissions are directly related to the amount of nitrogen applied. This relationship is however not clearly established, which is the second uncertainty.

The calculations on the amount of N_2O emissions are done following IPCCs (2007) recommendations. These state that if the site specific conditions are not rigorously well documented, default values on the different emission factors should be used. The true values of these EFs, however, vary considerably.

Figure 5.5 illustrates the change in total GWP when these two uncertainties are accounted for. The nitrogen content was set to 1.5 and 4 percent respectively and the total conversion of nitrogen was varied according to the minimum and maximum of the uncertainty ranges reported by IPCC (2007). Under what circumstances these extreme values of the EFs are to occur is however not stated in the IPCC report.

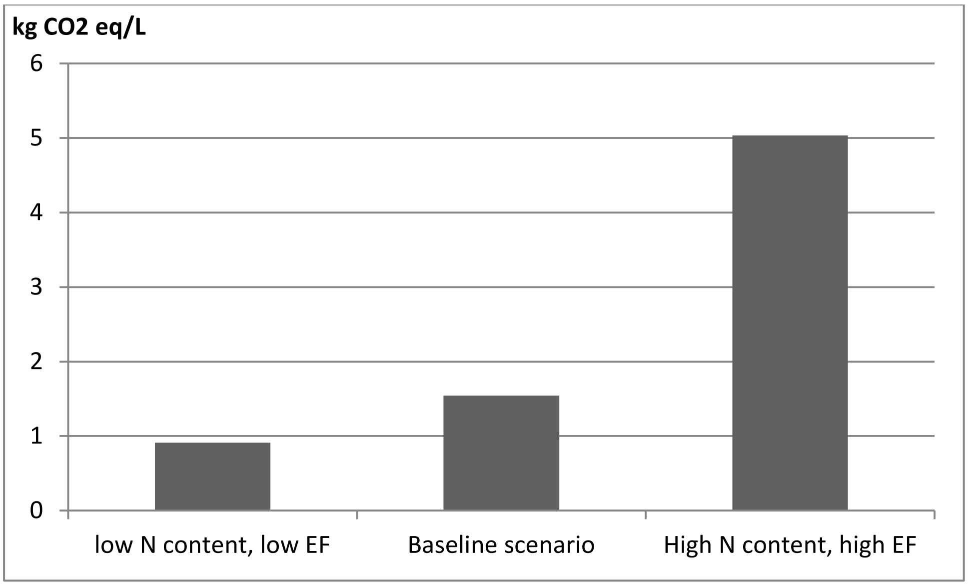

Figure 5.5. The total GWP of PPO as it varies with different nitrogen content of the seed cake and different size of the fraction which is converted to N_2O.

5.3 Fruit characteristics

The fruits that are picked at Luambala are sometimes yellow and mature while some have long since matured and have turned brown. If there have been heavy rains prior to the harvest, the brown fruits are very moist. The procedure for drying the fruits and seeds is not standardized and the water content therefore varies. In conclusion, all fruits are very different from each other when it comes to the weight ratios wet seed/fruit and dry seed/wet seed. This causes uncertainty as all calculations are based on an assumed yield measured in kg dry seed and the weight ratios are used to convert the numbers into different units.

The weight ratios used are based on small samples which do not give a reliable mean value. These measurements should have been carried out on a larger test sample. To investigate the sensitivity of the impact categories to the ratios wet seed/fruit and dry seed/wet seed are varied. They are varied together 20 percent down and 20 percent down to visualize a plausible range of the results from the impact assessment. The true value will depend on when the fruits are harvested and how they are dried.

None of the indicators for water use is affected by these factors, as theyare all related to the unit kg dry seed. The weakness of having to use these conversion factors however effects FEU and GWP, mainly because the weight ratios were used to calculate the efficiency of the cracker. This is visualized in figures5.6 and 5.7.

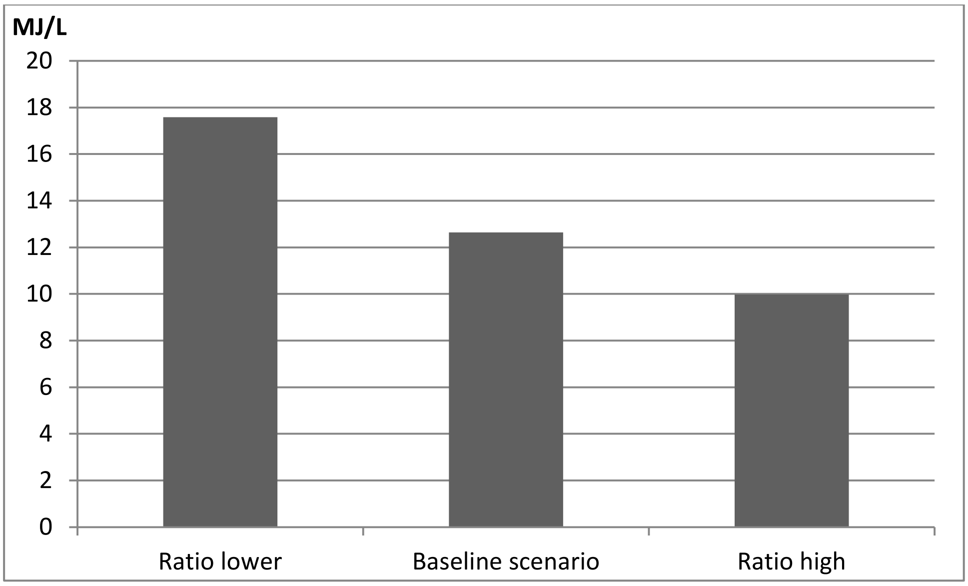

Figure 5.6. The total FEU is largely affected by the weight ratios wet seed/fruit and dry seed/wet seed.

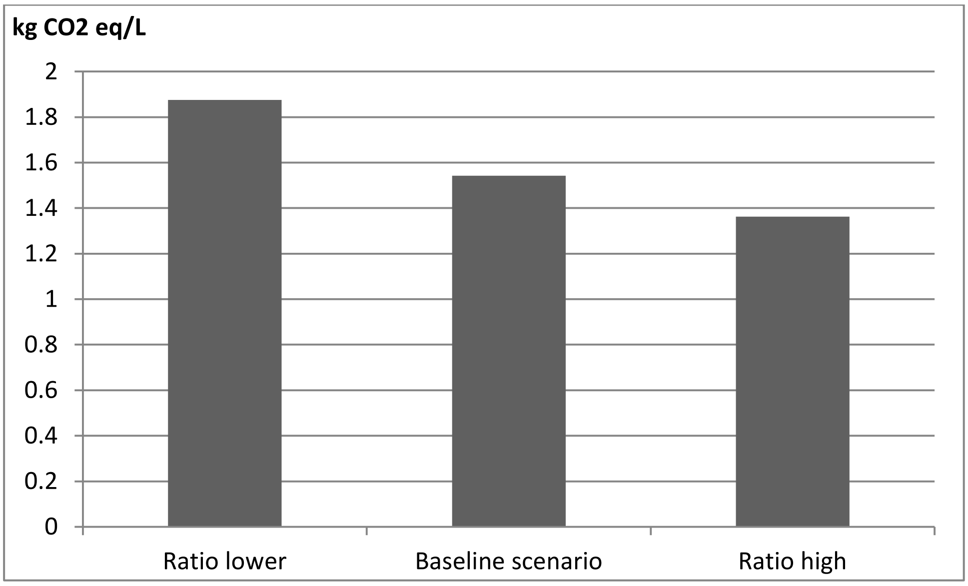

Figure 5.7. The total GWP as it is affected by the weight ratios wet seed/fruit and dry seed/wet seed.

5.4 PPO used within the system

All calculations in the inventory chapter of this study are based on the assumption that the fuel used at Luambala is fossil diesel. At the time of the field study no other fuel was available, but when production of PPO starts this will of course start to substitute the imported diesel. This will alter the results of this LCA. It is uncertain however, how much PPO that will be blended into the diesel and how this will affect the functionality of the engines.

As an example on how the life cycle impacts could change, it has been investigated mathematically how the fossil energy use would be altered if all fuel used would be a 50/50 blend of diesel and PPO (B50). Two factors will affect the results in this case: The first one is the diesel use per ha and per processed kg dry seed, which of course will be lower. The second factor is the volume of PPO that is transported from Luambala, the net production, which will also be lower. The indicator fossil energy use illustrates how these two factors are related, see figure 5.8.

5.4.1 Calculating the effects of using B50

First the current diesel use in the jatropha production system needs to be known. The total primary fossil energy use was calculated in the inventory chapter and can be converted into other units. All this energy, except that for chemical production, stemmed from diesel use. The total diesel use per ha is 79 litres, or 2770 MJ of secondary energy$\left(E_{Tot\ fuel}\right)$. Assuming this is the amount of energy needed, disregarding which fuel is used, the amount of B50 needed ($V_{B50}\ [L/ha]$) can be calculated. The calorific value of B50 is 38.4 MJ/L(Forson et al., 2004).

$$V_{B50} = \frac{E_{Totfeul}}{38{,}4} \quad (5.1)$$

Half of this volume is diesel and the other half is PPO that has been produced at Luambala, making the net yield Y_{Net}smaller.

$$Y_{Net} = Y - \frac{V_{B50}}{2} \times CF_{KgdryseedtoLPPO} \quad (5.2)$$

In equation 5.2$Y$is the yield and $CF_{Kg\ dry\ seed\ to\ L\ PPO}$ is the ratio of kg dry seed per L PPO produced. The lower net yield affects the allocation of impacts. Equation 5.2 changes to

$$CF_{HatoLPPO,B50} = \frac{CF_{kgdryseedtoL\ PPO}}{Y_{Net}} \quad (5.3)$$

which is used to calculate the new total fossil energy use

$$I_{TotFEU,B50} = \frac{V_{B50}}{2} \times EF_{DieselFEU} \times CF_{HatoLPPO,B50} +$$

$$+\left(I_{GlyphosateprodFEU} + I_{CipermitrinaprodFEU}\right) \times \frac{CF_{HatoLPPO,B50}}{CF_{HatoLPPO}} \quad (5.4)$$

The first half of equation 5.4 calculates the primary energy use of the diesel by the same emission factor as in the inventory and the new conversion factor. The second half adds the fossil energy use of producing the chemicals sprayed on the fields, adjusting for the new CF. The impact of the chemical production is calculated by equation 3.27. The result of the calculations is presented in figure 5.8.

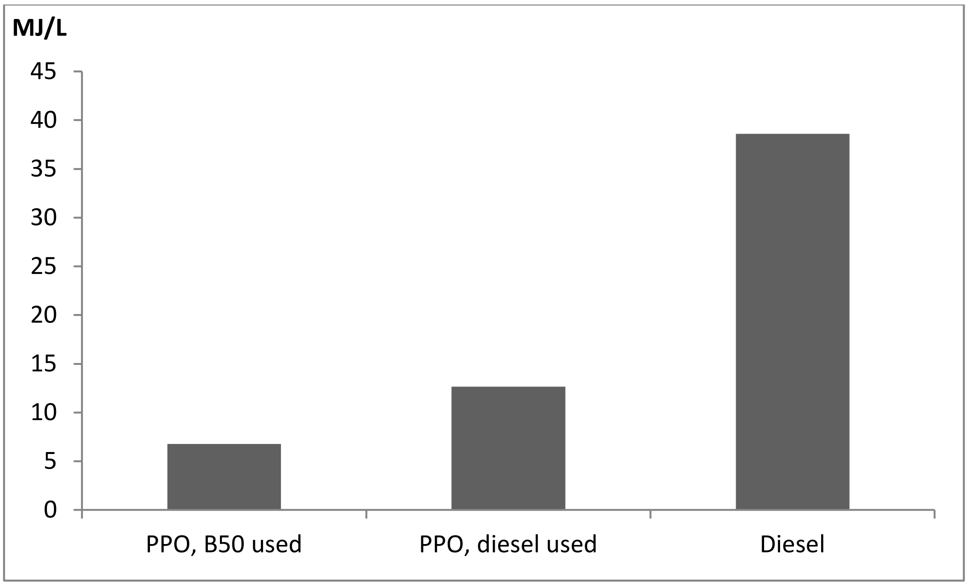

Figure 5.8.A comparison of the fossil energy use of three scenarios. The middle and right bars are the same results presented in the impact assessment. The left bar represents the fossil energy use of producing PPO, using B50 instead of diesel in all relevant processes.

There is a clear reduction of the fossil energy use when using B50, improving the long term performance of the jatropha production system. Because a goal of the plantation is to reduce the dependency of imported diesel this is good news. The results indicate that the plantation can be more self-sustaining than it currently is. Assuming B50 use is a more relevant long term scenario and it seems to be a scenario with better environmental performance.

6 Discussion

All the results are discussed in chapter six and the discussion is divided into the different impact categories; fossil energy use, global warming potential and water use. The effects of land use change and CO_2 emissions from burning biomass are also discussed. This chapter also discusses possible future developments of the jatropha system; the advantages and drawbacks of producing JME instead of PPO, the possible logistics improvement of using an outgrowers scheme and the potential economic improvement of selling carbon credits.

6.1 Fossil energy use

The plantation preparation phase is the phase where there is largest uncertainty about the functionality. This is because no nursery had yet been established at the time of the field study and the establishment will much be based on "trial & error". But, as is seen in figure 4.2, this phase contributes very little to the total FEU.

The plantation phase of the production system is the most thoroughly investigated phase of the jatropha production system, much because of availability of data. It is also the phase with most sub-processes. This phase however only accounts for about one seventh of the total FEU of producing PPO. This supports the idea that cultivating jatropha does not have to be energy intensive and might have good environmental performance. However, the various impacts and costs of producing PPO lie elsewhere in the system.

The main energy use is when cracking the fruits and pressing the seeds. That these two steps are energy intensive is no surprise as these steps are mechanized to a higher extent than the field works of jatropha cultivation at Luambala. It is however surprising how these steps dominate the total FEU. An explanation for this could be that the machines are oversized and therefore not used efficiently. The rather small cracker is powered by a large tractor and the generator powering the oil press runs on only twenty percent load.

At the time of the field study, an electric motor for at least one of the crackers was due for delivery soon. With this installed, the cracker has the potential to be more efficient than the tractor currently used. It is worth noting that cracking of fruits can be done entirely manual or by driving the cracker by hand power. This is of course more labor intensive, but in Mozambique unqualified labor is cheap and diesel is expensive.

The energy use of the oil press is significant and if the crackers are fitted with electric engines the electricity consumption of Luambala will increase further. Connecting these machines to the grid would drastically lower the FEU as the grid power in Mozambique is entirely hydropower, mainly from the large Cahora Bassa dam on the Zambezi River (RECIPES, 2006). But as the expansion of the power grid is very slow, it is perhaps easier to move at least the oil press to the grid in Lichinga.

6.2 Global warming potential

Most emissions of CO_2 is due to the burning of diesel, see above for a discussion about this. In this production system, CO_2 from fossil fuels is however not the most interesting. Instead, the largest contributor to GWP is the emissions of N_2O, which is not uncommon for agricultural products (Edwards et al., 2007).

There are direct emissions of N_2O from the soil when nitrogen is added to the fields as well as indirect emissions when N_2O is formed from nitrogen compounds that have leached or volatilized from the field. The total emissions can vary considerably depending on natural factors and the nitrogen management (IPCC, 2007). Applying the correct management principles will lower the amount of nitrogen not utilized by the plant and therefore also lower the emissions of N_2O (Lilly, 1991). It is not rare that GWP for Biofuels are about 30-50 percent of the GWP for fossil diesel (Arvidsson et al., 2010).

6.2.1 Land use change

In this study, no impacts from land use change have been considered. It is however not irrelevant to consider the change in carbon content of soil or above- and below-ground biomass when a jatropha plantation is established. This has been done by e.g. Reinhardt et al. (2007) who concluded that if land use changes are included, the GWP for JME might actually be higher than that for fossil diesel. But, this is dependent not only on the alternative land use but also on how one chooses to allocate the emissions. For this allocation, there is no scientific consensus other than that it matters.

According to Reinhardt et al. (2007), there is a big difference in GWP if the plantation is established on previous wasteland or forestland. Luambala is mostly surrounded by managed natural forest with dense grass undergrowth. Traditionally, mainly firewood is gathered from this land as well some wild fruits. The firewood is still needed even though the forest is cleared and there might be complications due to indirect land use change, that trees are felled elsewhere to provide the firewood. As mentioned earlier, it seems that a lot of branches are taken from the plantation, probably for this purpose, which lowers the risk of forest degradation elsewhere. To quantify the amount of firewood needed in the proximity of the Luambala farm or the extent of branch theft is however not done in this study.

A positive effect of the plantation establishment is the fire prevention. Every dry season in Niassa there are large grass fires. Many are intentional to clear land for agriculture or to keep away snakes, but the fires often spread out of control. This fire prevents the soils from accumulating much carbon and is of course harmful to most trees. Even though thecarbon in biomass or soil organic carbon is not quantified within this study, it is reasonable to believe that they are not very high in Niassa. The main positive effect of the Luambala farm regarding GWP, would then be that fire prevention at the farm, to protect the jatropha, will increase the carbon in biomass both at the farm and in its proximity. The best way to protect crops from grassfires is, after all, to prevent the fire from ever starting. This would then be a positive indirect land use change, as the decrease in burning might enable the growth of biomass elsewhere.

6.2.2 CO_2 emissions from biomass burning

Biofuels are traditionally considered to be climate neutral when combusted as the carbon released was once assimilated from the atmosphere and that this combustion is a part of the carbon cycle. A recent paper by Cherubini et al. (2011) however reasons that the CO_2 will contribute to climate change the time that it is in the atmosphere instead of in biomass. This time is related to how quick the biomass will regrow. The article also presents how the GWP of the biomass burning should be calculated. For a crop such as jatropha, which is harvested every year, the increased GWP is negligible, but for a slow growing crop or forests, this factor should be reckoned.

The reasoning by Cherubini et al. is also interesting in combination with that of land use change, as they both deal with anthropogenic disturbances of natural carbon cycles instead of net additions of carbon by burning of fossil resources. As jatropha is cultivated for a thirty year period it will assimilate carbon in other parts of the plant than the fruits that are harvested annually. This assimilated carbon might be more than the carbon assimilated by the grass that will burn annually. Further investigation of these indirect effects is of interest to fairly assess the GWP of biofuels.

6.3 Water use

The results of the water use assessment are discussed in this section. Water use assessment in life cycle assessment in general is also discussed.

6.3.1 Water footprint

One reason for the large differences in water footprint for the reference system and the jatropha production system is that for the water footprint, evaporative losses during crop growth are included and thus making the green water footprint the largest contributor. In the fossil reference system only blue water consumed in the process has been accounted since the use of cooling water is not considered as a consumptive use. When comparing the blue water footprint for the two studied systems, the blue WF for the jatropha production system is almost half of the blue WF for the diesel production system. Since blue water use is considered as less sustainable than the green water use (Peters et al., 2010), it is difficult to compare these in terms of environmental impacts.

The result of the total water footprint in this study, 23. 5 m^3/L PPO, can be compared with the result obtained in the study by Jongshaap et al. (2009) which was only 8.3 m^3/L PPO, using no irrigation and having almost twice as high yield which is a possible explanation for the higher WF of this study. The result can also be compared with the water footprint for jatropha biodiesel calculated by Gerben-Leenes et al. (2009) whoassessed the water footprint of 13 different bioenergy crops and found that jatropha had the largest water use among them, 20 m^3/L JME. The water use during the transesterification step can be neglected since no water is used during this step and the result are thus similar to the result found in this report.However, in the work by Jongshaap and colleagues (2009), the authors argue that the comparison of the jatropha water use with the other proposed bioenergy crops, in the study by Gerben-Leenes et al. (2009),is not fair. Since the compared crops only can utilize fertile land whereas jatropha is able to grow on wasteland, they are according to Jongshaap et al. (2009) not comparable. The results obtained in the study by Gerben-Leenes et al. (2009)does not regard the benefits of jatropha being water efficient and not competing with food production. Therefore, the crops should not be compared as by Gerben-Leenes and collegues (2009) according to Jongshaap et al. (2009).

6.3.2 Local hydrological cycle deviation

The water use assessment shows that the LHCD for the jatropha production system is much lesser than the result of the water footprint for the same system. The largest reason is that the LHCD does not account rain water as consumptive use since it is not leaving its local hydrological system. In this case study, the water used to dilute pesticides and herbicides is also neglected. The reason is that the water used for this performance is assumed to be withdrawn from the nearby Luambala River and when this water is evaporated, it is assumed that it returns to the local hydrological system.

The LHCD is much smaller for the jatropha production system than for the fossil reference system according to the results of this study. Factors that could change the results are the accounting of dilution water and possible plantation irrigation water taken from a distant origin. The LHCD for the fossil reference system is calculated in the same manner as the production of fossil diesel used within the jatropha production system. The same assumption that the processing water is blue/fund water is applied. The origin of the process water used in the fossil diesel production is however not known. It is important to consider the aspects ofpossible environmental damage when usingprocessing water from the unknown source compared to the use of water from the Luambala River. The indicator *local hydrological cycle deviation* only indicates the amounts of used water affecting the local hydrological cycle and it does not yet link results to environmental risks.

6.3.3 Water use assessment

To assess water use in a life cycle assessment is a complex task and clear definitions of the sources of water are needed. No agreed indicators for water use are yet fully established.Currently, the use of different indicators in literature and scientists disagreements on water sources is confusing and results are not comparable. Gregory Peters and colleagues commented on this problem in the paper about water accounting for Australian red meat production in L water/kg beef produced (Peters et al., 2009). They found that results from several scientific papers differs too much and address the problem with managing use from different water sources.

How to account water use in different parts of the world, e.g. water scarce areas, should gain more attention in literature and anorganizedsystem to solve this problem is needed. Abou Kheira and Atta studied the effects of different water stresses for jatropha and how it affects the oil yield. They found that the oil yield decreased more with oversupply of water than undersupply and is thus an indication of jatropha being a water efficient plant, not as affected by undersupply of water as first believed (Abou Kheira and Atta, 2008). Göran Berndes comments in his paper that even if the water footprint is developed to communicate between nations, it requires an understanding and an expertise in the area to fully understand what the number means (Berndes, 2010). No conclusions can be drawn from the water footprint result unless the result is put in its right context.

As presented in this study, the thoughts of how to consider precipitation have been widely discussed in literature. Should rainwater be considered as a free resource or as an actual water use? The evaporation losses during the production system are also discussed and Milá i Canals and colleagues argue that evaporation should be considered as a consumption of water (Milá i Canals et al. 2009). In the definition of the LHCD, developed in this study, evaporative losses are only accounted when occurring far away from the local hydrological cycle. How evapotranspiration should be considered in agricultural systems when doing water use assessment needs to be further discussed.

Compared to other impact categories, the water use is often regarded as a resource category only, and has no clear relation to environmental impact. Still, the quality of water may also be of interest to consider (Peters et al., 2010). The quality should however be accounted for in a way which avoids double counting when also assessing, for example, eutriphication and toxicity.

6.4 JME vs PPO

When Chikweti started up the jatropha project, the aim was to produce biodiesel of the jatropha oil. They received money from NUTEK and SIDA to subvert the project, which is a collaboration between Chikweti Forest of Niassa and Ageratec AB. Ageratec is a Swedish company producing biodiesel processors and other equipment related to biofuel production. From Ageratec, Chikweti has received a biodiesel processor, an oil press, an electricity generator and other equipment associated with the possible future production (Ageratec, 2011a). At the moment, the oil press is installed and the pressing of the jatropha nuts will begin soon. In this study only the production of jatropha oil has been assessed. In this section, the possibilities of a biodiesel production and the potential benefits/drawbacks of this production are discussed.

6.4.1 Biodiesel production

The processor that Chikweti has received from Ageratec is the model PE 3000 which is the largest processor that the company retails with a production capacity of 3000 L biodiesel/ day (Ageratec, 2011b).

To produce biodiesel, the crude jatropha oil, the PPO, needs to be processed into JME (jatropha methyl ester). It exist several techniques to produce biodiesel out of vegetable oil but the most common is by the transesterification process which is the one used by the processing unit PE 3000 (Ageratec, 2011b). Transesterification is the process where triglycerides react with alcohols to form methyl-/ethyl esters forming glycerol as a by-product. Normally this requires methanol as a reactant and a solvent, water and probably a catalyst (Nazir et al., 2009). There are many kinds of catalysts suitable for this reaction and the PE 3000 uses sulphuric acid and potassium methylate as catalysts (Ageratec, 2011b). The transesterification is performed in three steps; first the triglyceride is converted to diglyceride, then converted to monoglyceride and finally into glycerol and in each step one molecule of methyl-/ethyl ester is formed. The steps are all equivalent and reversible (Nazir et al., 2009). A cleaning agent (PAC) is used to clean the biodiesel from excess ions and to remove water. The processes, inputs and outputs are visualized in figure 6.1.

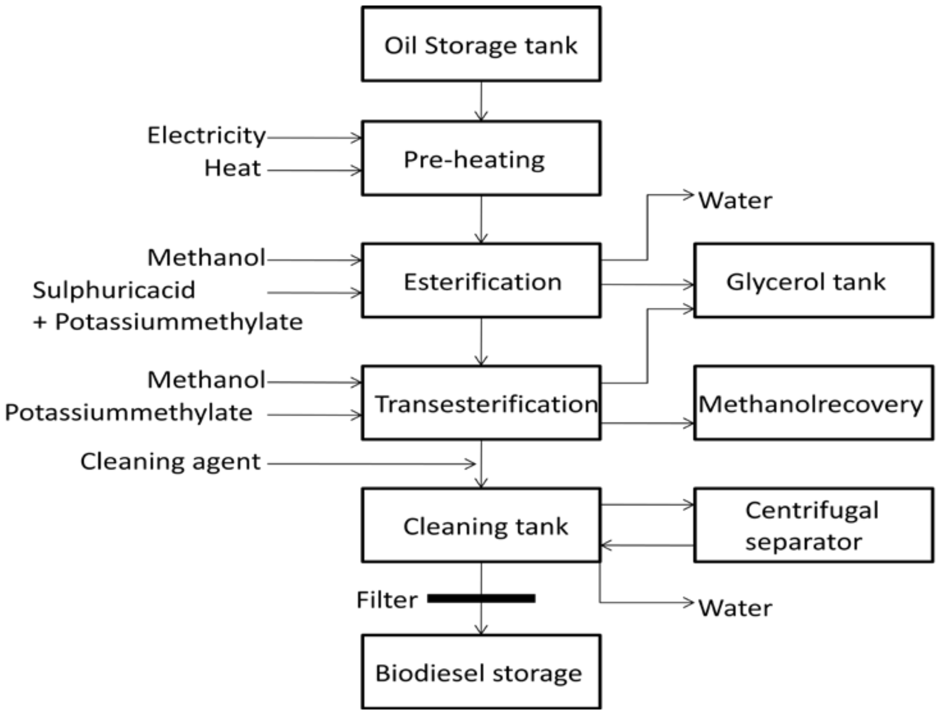

Figure 6.1.A schematic representation of the processing steps, the inputs and outputs in the biodiesel processor PE 3000.

The inputs are jatropha PPO, methanol, sulphuric acid, potassium methylate, cleaning agent (PAC) electricity, heat and water. The outputs are JME, glycerol, water and emissions. The glycerol can be used as a feedstock in other processes like soap, medicine and cosmetic production (Prueksakorn and Gheewala, 2006). Per liter PPO processed the consumption of chemicals equals the presented numbers in table 6.1.

Table 6.1. Inputs and outputs to the PE 3000 per liter PPO consumed (Ageratec, 2011b).

Raw material requirements and outputs	
Consumed per L PPO	
PPO [L]	1
Methanol [L]	0.15
Potassium methylate [L]	0.01
Sulphuric acid [L]	0.01
Cleaning agent [L]	0.004
Electricity [kWh]	0.065
Produced per L PPO	
Glycerol [L]	0.18
JME [L]	0.8

The water content of the PPO should be kept as low as possible to reduce the effect that water causes ester saponifiation (Nazir et al., 2009). According to a contact person at Ageratec, Ulf Johansson, the only water used in the process is the water used to operate the centrifugal separator that corresponds to an amount of a couple of hundred liters per week (Johansson, 2011).

6.4.2 Benefits vs. drawbacks of producing JME

If it is beneficial or not to produce JME depends on economical, environmental and resource factors. Producing JME would increase material and maintenance costs as well as labor costs. An advantage to produce JME is that it can be used in any diesel engine without any further adaption. When transesterified, the viscosity is reduced and thus suitable for direct use in an ignition engine. A study made by Rahman et al. (n.d) showed that the use of JME in a diesel engine improve the lubricity and result in lower emissions compared to fossil diesel. A disadvantage with producing JME is the need for very clean PPO before it enters the process. It should not contain any impurities and those should first be removed and thus demand a cleaning process (Beerens et al., 2010). This can be a complicated task. A jatropha oil project run by FACT in northern Mozambique had problems with the quality of the oil. They sent newly pressed jatropha oil for experimental examination which concluded that all critical values were too high to be used in engines as PPO or used as a feedstock for biodiesel production (Nielsen et al., 2011)

As can be seen in table 6.1, the processor needs a lot of chemicals and energy to process the PPO into JME. The production of these input demands are associated with costs and emissions that needs to be added to the calculations.An LCA has been conducted by Esteban et al. (2011) to compare the advantages and disadvantages to use pure vegetable oil or biodiesel made of rapeseed. They looked at the fuel consumption in a truck and the energy efficiency was compared. The study showed that it is environmentally feasible to use vegetable oil instead of biodiesel. The transesterification step showed large contributions to the GWP and ozone depletion potential because of the chemicals used. They strongly recommend to not producing methyl esters and instead use blends of vegetable oil (Esteban et al., 2011).

As mentioned before, jatropha PPO can be used directly after pressing without any further processing in some engines (Deutz, Hatz, IFA, Elsbett, DMS, Farymann and Lister-type) (Beerens et al., 2010, Prueksakorn and Gheewala, 2006, Heller, 1996). But using straight vegetable oil in an ignition engine is not favorable due to the high viscosity which could lead to agglomeration and incomplete fuel combustion (Misra and Murthy, 2010, Chahuan et al., 2009). A good alternative is thus to blend the jatropha PPO with diesel. The savings in fossil diesel costs would thus equal the amount of PPO replaced minus the production costs of PPO. Due to calorific content and differences in viscosity, the blend of PPO in fossil diesel needs to be carefully chosen. Misra and Murthy (2010) made a study of different vegetable and diesel blends in an ignition engine and found that a blend of 10 percent vegetable oil is favorable and actually shows better results than using pure diesel with improved thermal efficiency and reduced exhaust emissions (Misra and Murthy, 2010). A study made by Pramanik (2002) showed that blending 40-50 percent jatropha oil in fossil diesel is highly acceptable and no modification of the single cylinder diesel engine needs to be done (Pramanik, 2002). A suggestion is to test different blends up to maximum 50 percent PPO to see which blend is most suitable for the intended engines. This temporary solution will however not eliminate our dependence of fossil energy, but the consumption would decrease.

6.5 Outgrowers scheme

The yearly fossil diesel consumption of Chikweti is about 650 000 L/year and the purchase of it is their largest expense. The purpose with the investments in jatropha biofuel production, they claim, is to be self-sustained of fuel. Due to lower energy content of JME, the demand would be to produce about 696 000 L/year and that correspond to a needed jatropha plantation area of 2700 ha assuming an average yield of 1.2 ton seeds/ha. The energy content of PPO is however higher than fossil diesel due to a higher density. If it was possible to substitute 100 percent to PPO, the demand of fuel would be only 628 000 L/year. In a hypothetical scenario, this would demand an area of 1900 ha assuming the same average yield of 1.2 ton seeds/ha. Luambala has a goal to expand the current jatropha plantations to 450 ha in the nearest future, and only producing PPO using 450 ha would make it possible to produce enough PPO to blend 23 percent PPO with 77 percent fossil diesel.

Chikweti also has plans to produce enough biofuel to sell surplus fuel to the petrol company Petromoc. If these two grand plans are to be realized, the plantations need to be expanded and one way to increase production is to use an out-growers scheme. The principle with this ownership model is that some or all production is outsourced to local farmers who cultivate jatropha on their own land and then sell the harvested fruits or seeds to Chikweti who produces the jatropha PPO.

As a part of the study, an interview was conducted with the local firm Mozambique Leaf Tobacco operating from Lichinga. They produce and sell tobacco and their main production system is an out-growers scheme. Employed technicians tour the nearby areas, campaigning the principle and asking families to join the team and start producing tobacco on their fields. When a family agrees to join and signs the contract, the technician teaches them the management and gives them tobacco seeds and fertilizers. The family then starts propagating tobacco and when it is time to harvest, the family harvest the tobacco and freights it to one of the company’s collection centers. Mozambique Leaf Tobacco purchases the harvested tobacco from the nearby families at the collection centre and then transports it to the factory in Lichinga. The advantages with using this production scheme, according to the company, are that it creates job opportunities for the local families and help them developing a business sense.

There are five different types of ownership models for jatropha PPO production; pure plantation, pure out-growers, pure farmer-owned, own plantation plus out-growers and farmer participation in production. The pure plantation model is common when foreign companies invest in land and start managing the area for jatropha production as in the case of Chikweti. The pure out-grower model describes the principle of a company signing contracts with local farmers to start producing jatropha and selling the harvest to the company, the principle that Mozambique Leaf Tobacco has adopted. The pure farmer-owned model is extremely rare when it comes to jatropha oil production. Both the plantations and the processing plant is operated and owned by the local farmer or an enterprise investing in the production. The hybrid model with own plantation and using outgrowers is the most common model and includes both an own plantation and an out-growers scheme. The last owner model describes the case of local farmers investing in the jatropha producing company's enterprise. This principle exists but is very rare (Moers, 2010).

The out-growers scheme is applicable to the production of jatropha PPO or JME at Chikweti. Today they have a pure plantation model of soon 450 ha, but if they want to meet the demand, the production needs to expand. The plausible scenarios of jatropha seed production would be either to expand their own plantation area and keep the ownership model they use today, or signing contracts with local farmers starting to produce the excess needed harvest using the hybrid model or abandon the existing jatropha plantation and only stake on pure out-grower model. The choice will be based on a balance between costs and risks. Investing in area for expanding plantations results in high start-up costs but the building-up of the logistics with out-grower scheme is also associated with costs. Investing in pure out-grower model increases risks because the lack of feedstock control, but on the other hand, large plantations in one place increases risks of crop failure (Moers, 2010).

The best balance between costs and risks would probably be to have both a plantation and an out-growers scheme. For Chikweti, however, an existing logistic problem is associated with the jatropha JME production. The jatropha plantation is located in Luambala as well as the oil processing site. Chikwetis centre of operations and the JME processing plant is located in Lichinga, 80 km from Luambala. When determining the centre of operations for the PPO production there are pros and cons with choosing either one.

Lichinga is good because of its location and transportation potential. The cracker and the oil press should be placed near the collection centres to reduce transportation costs and should thus be installed in Lichinga. However, since the present jatropha plantation is located in Luambala, the relocating of the cracker and the oil press to Lichinga would increase their transportation costs from Luambala to Lichinga with a factor of almost 20, also assuming that instead of transporting pressed jatropha PPO, the harvested fruits are transported. If instead of using a cracker, the seeds are cracked open by hand and dried in sunlight before transportation to Lichinga, the transportation costs would only increase by a factor of five.

There is however uncertain if the jatropha bushes can thrive at the high altitudes around Lichinga. Perhaps it is better to recruit out-growers in the areas surrounding Luambala, even if this means more difficult transportations. And again, it is perhaps a good choice to crack the fruits by hand at the site of harvest.

A recommendation to Chikweti, is to expand their own jatropha plantation to the planned 450 ha. The rest of the area needed to produce enough PPO to be self-sustained (1450 ha), is better to locate to local farming production using an out-grower scheme. The oil press would then best be located in Lichinga because of the accessibility. To reduce transportation costs, the present cracker should be located in Luambala to be used by Chikweti and nearby farmersonly. Other out-growers with small production could crack the fruits by hand or invest in a small cracker.

6.6 Carbon credits

Within Chikweti, the opportunity to earn money on registering the jatropha plantation and the biofuel production to the carbon credit fund, has been discussed. The sequestration of carbon by the jatropha trees could earn the company carbon credits, which can be sold to other companies and thus helping the overall reduction in carbon emissions in the world. An example of a calculation of carbon credits for a jatropha plantation is discussed in this section and should only be considered as an example.

A study made by Firdaus et al. (2010) examined the sequestration of carbon for Jatropha. The method was to measure the litterfall, the biomass production and the canopy photosynthesis. The study showed that the jatropha tree mostly sequestrates carbon in the aboveground mass. Their tests showed that the sequestration rate is 13 Mg C/ha with a planting distance of 2x3 m (Firdaus et al., 2010).This would correspond to a sequestration rate of 7.8 kg carbon/plant/year. If Luambala would increase their plantations to the possibly 450 hectares, with a planting distance corresponding to 2500 jatropha plants/ha, the amounts of sequestrated carbon per year would be about 8 800 ton and thus saving around 32 000 ton CO_2. Looking for example at the short term CER which costs 5-20 €/ton CO_2, the earnings of using carbon credits for the jatropha plantations would be around 160 000-640 000 €/year.This calculation is only an example and every aspect is not considered, such as possible carbon debt of clearing land for plantations. There is also a possibility to earn carbon credits on biofuel production, but this is more complicated and should be further examined (Bakker, 2006).

Jatropha plantations have, according to a jatropha project in South Africa, all requirements to be used within the CDM and carbon credits (Jatropha.org.za, 2008). But what is important to consider is the baseline scenario. The natural forests are cleared to give space for jatropha plantations. This creates a negative carbon baseline scenario since the carbon sequestrated in the previous occurring biomass is emitted into the atmosphere. This “carbon debt” first needs to be paid off by the new plantations before any earnings can be accounted.

To be a member of a carbon credit fund could be costly. Some funds have a yearly participation fee and a registration cost per ton sequestrated carbon (Marquis, 2011). When deciding which fund to join, such costs needs to be noted and a complete cost estimate should be done.

The carbon credits market seems complicated, but the possibilities to save money do exist. Chikweti also has large plantations of pine and eucalyptus. A contract including pine tree- and eucalyptus tree plantations for timber and jatropha plantations and biofuel production would make a difference for the economy of the company. Appropriate cost calculations should be performed by a consultant before making any decisions on carbon credits.

7 Conclusions and Recommendations

Based on the obtained results and discussions, the last chapter presents the final conclusions of the master thesis. Recommendations to Chikweti and future scientific work based on the conclusions are also stated.

Based on the case study, the literature study and the results of the life cycle assessment the following conclusions of the master thesis could be drawn:

- Using jatropha PPO instead of fossil diesel reduces the emissions of green house gases and use of fossil diesel.
- The water footprint for jatropha is higher than for other bioenergy crops and the results of this study show higher water footprint than other studies of jatropha. The results vary considerably between different water use indicators in this study and in general.

- Jatropha curcas linnaeus is not a wonder crop regarding production of bioenergy, but requires good agronomic practices.
- The yield is an important factor and a big challenge for this un-established bioenergy crop. Agronomic science and knowledge needs to be developed.
- To avoid depletion of nutrients in the plantation soil, the seedcake should be used as fertilizer.
- Oil processing can be energy demanding. The use of small generators and tractors to power equipment is inefficient and should be minimized.
- As long as the production of PPO is low, no JME should be produced. Producing JME costs and requires more input than using just PPO. The PPO can be used blended in fossil diesel or straight in some engines, such as generators.

- There is no present agreed upon method on how water use should be assessed in an LCA. Future development is needed to be able to find a clear relation between water use and environmental impact.
- Studying the impacts of an agricultural production system should include the aspects of land use change to be fair. Especially global warming potential can be greatly affected by the alternative land use and indirect land use change.

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Appendix

Input data used in the calculations are presented here.

Water use

Input data to CROPWAT 8.0 for calculations of the crop water use.

Table A1. Input parameters for the calculation for irrigation needed in nursery and the amounts of rain water used until first harvest, that is from 15/8-10/3 (Sutterer, 2010).

Input data to CROPWAT	**From 15/8-10/3**				
Input parameters	Initial stage	Development	Mid-season	Late season	Total
Duration in days	43	60	30	75	208
Kc-value	0.6		1.2	1.2	
Rooting depth [m]	0.3		1.2		
Crop heigth [m]			3		
Critical depletion fraction	0.4		0.4	0.4	
Yield response factor	0.5	0.5	1	1	

Table A2. Input parameters for the calculation of crop water requirements and amounts of rainwater used on the field from first harvest to the age of 1 year, from 10/3-15/8 (Sutterer, 2010).

Input data to CROPWAT	**From 10/3-15/8**				
Input parameters	Initial stage	Development	Mid-season	Late season	Total
Duration in days	46	1	107	5	159
Kc-value	1.2		0.15	0.15	
Rooting depth [m]	0.3		1.2		
Crop heigth [m]			3		
Critical depletion fraction	0.4		0.4	0.4	
Yield response factor	0.5	0.5	1	1	

Table A3. Input parameters for the calculation of crop water requirements and amounts of rainwater used on the field from first harvest from year 2 to 30 (Sutterer, 2010).

Input data to CROPWAT	**From 15/8-15/8**	**From year 2-30**			
Input parameters	Initial stage	Development	Mid-season	Late season	Total
Duration in days	46	1	242	76	365
Kc-value	0.15		1.2	0.15	
Rooting depth [m]	0.3		1.2		
Crop heigth [m]			3		
Critical depletion fraction	0.4		0.4	0.4	
Yield response factor	0.5	0.5	1	1	

Table A4: The rain data provided by the weather station in Lichinga from CLIMWAT 2.0.

Climate data, Lichinga		
Rainfall (Cropwat, red, sandy soil)	Rain (mm)	Eff rain (mm)
January	222	143.1
February	221	142.9
Mars	192	133
April	89	76.3
May	23	22.2
June	3	3
July	4	4
August	1	1
September	3	3
October	20	19.4
November	99	83.3
December	236	146.9