Master's Thesis:

Economic and environmental assessment of different forestry biomass to bioenergy conversion configurations in the South-eastern USA region

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Abstract

In order to limit the global mean temperature increase, efforts need to be made to reduce greenhouse gas (GHG) emissions. A commonly recognized strategy to reduce GHG emissions is by replacing fossil fuels by renewable energy sources. In this thesis different potential biomass to bioenergy configurations for the Southeastern USA region are explored, and the costs and GHG emissions involved in the bioenergy production are compared to the costs and GHG emissions of the fossil fuels which they can substitute. The feedstocks Loblolly pine and mixed natural hardwood are selected as biomass, and the five conversion technologies pelleting, TOP process, hydrolysis and fermentation, gasification and FT and pyrolysis are selected. The ten configurations produce different bioenergy types which are able to substitute coal, gasoline, diesel or a mix of gasoline and diesel. The costs and GHG emissions for the processes cultivation, harvesting, transport and processing are first calculated separately and after combined to find the supply chain costs and supply chain emissions for each configuration. The feedstock mixed natural hardwood is, under the assumptions made in this thesis, not economically interesting to be used for bioenergy production due to high discounted cultivation costs of 25.81 $/GJ biomass, compared to 1.93 $/GJ biomass for Loblolly pine. Due to the selected management practices the cultivation of hardwood however has no GHG emissions. The costs and emissions involved in harvesting are similar for both feedstocks, and only represent a smaller share in the total supply chain costs and GHG emissions. The costs and GHG involved in the transport of hardwood are higher due to the larger transport distance of the biomass. In the processing costs of the conversion technologies the pelleting and TOP process result in the lowest costs, while fermentation and gasification have the lowest GHG emissions. Two different scenarios' are applied in order to compare the bioenergy to the reference fossil fuels. First the GHG emission reduction due to the conversion of 1 tonne biomass in the different configurations is calculated finding that the pelleting, and after the TOP process configurations lead to a GHG emission reduction of approximately 1200 to 1500 kg CO_2-eq per dry tonne biomass. Following, the cost difference between bioenergy and its fossil fuel reference is divided by the GHG emission reduction of bioenergy compared to the fossil fuel. For the configurations using hardwood this scenario leads to high GHG emission reduction costs due to the high costs of the biomass. For the remaining loblolly pine configurations the pelleting technology leads to the GHG abatement costs.

1. Introduction

The global energy demand has increased rapidly in the recent decades, and is expected to further increase over the years to come. The global primary energy demand has grown by 76% from 1980 to 2010, and is projected to grow by an average annual rate of 1.2% between 2010 and 2035 if government policies remain unchanged (IEA, 2012). The CO_2 emissions from fossil fuel use and industrial processes have caused 78% of the total greenhouse gas (GHG) emission increase between 1970 and 2010 (Eickemeier et al., 2014), and if no additional efforts are made to reduce these global GHG emissions, they are expected to further increase. This is projected to lead to a global mean temperature increase of between 3.7℃ and 4.8℃ compared to pre-industrial levels (Eickemeier et al., 2014). In order to limit the global mean temperature increase by 2100 to 2℃, both energy intensity and carbon intensity should be improved (Eickemeier et al., 2014). One of the most widely recognized strategies to reduce the carbon intensity is by utilizing renewable energy sources such as biomass. This strategy is projected to deliver a substantial increased share in renewable energy in the future (IEA, 2012). Cornelissen et al. (2012) performed a life cycle analysis to show that the use of bioenergy1 instead of fossil fuel in 2050 could lead to a GHG emission saving of 75-85% (Cornelissen, Koper, & Deng, 2012). Furthermore, Valentine et al. (2012) state that the production of bioenergy has four main gains for society: a reduction in GHG emissions2; increased energy security due to lower fossil fuel dependence; potential to stimulate rural and urban economic development; and a reduced carbon footprint of the agricultural sector. The contribution of bioenergy on the reduction of GHG emissions however depends on the efficiency of the biomass-to-energy system, the land use management and the local governance (Eickemeier et al., 2014).

Modern bioenergy[3] can be produced from different types of biomass by applying thermochemical, biochemical (Wright & Brown, 2007b) and thermal processing technologies (Mcdow, 2013). A general distinction is made between first and second generation biofuel feedstocks. First generation biofuel feedstock concerns the parts of crops that contain sugars, grains or seeds that can be converted into bioenergy by relatively simple conversion processes (GEA, 2010). The main disadvantage of feedstock for first generation biofuels is that it often uses the edible portion of a crops causing raises in food prices (Naik, Goud, Rout, & Dalai, 2010). Second generation biofuels are produced from lignocellulosic biomass which is non-edible (GEA, 2010) and therefore have an advantage over first generation biofuel feedstock (Naik et al., 2010). According to OECD second generation biofuel crops and conversion technologies are more efficient than first generation biofuel crops and conversion technologies, leading to a significant higher GHG mitigation potential (OECD, 2010). Furthermore, second generation crops have the potential to make use of abandoned land, which is often unsuitable for first generation crops (Naik et al., 2010). Using lignocellulosic biomass has the additional advantage that feedstocks with different harvesting windows could be used allowing for all year around harvesting (Ekşioğlu, Acharya, Leightley, & Arora, 2009). This ensures a high utilization factor of the harvesting, transport and conversion capital (Thorsell, Epplin, Huhnke, & Taliaferro,

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1 Bioenergy is defined as a renewable energy which is derived from biomass, and can be used as biofuel, or for the production of heat or electricity (http://www.ers.usda.gov/topics/farm-economy/bioenergy.aspx)

2 Bioenergy is often considered to be carbon neutral since the emissions from the combustion of bioenergy have previously been absorbed by biomass during its growth. The UNFCCC (2006) has called this the carbon neutrality assumption.

3 The total global primary energy consumption of biomass in 2013 was approximately 57 EJ, of which around 60% was traditional biomass, and the rest was used for the production of modern bioenergy (REN21, 2014). Traditional biomass is defined as biomass used for direct combustion, while modern bioenergy are more convenient solid, liquid and gaseous secondary energy carriers created by the conversion of biomass (Edenhofer et al., 2012).

2004). The necessary conversion processes for second generation bioenergy are however more complex (Naik et al., 2010).

The current production of liquid biofuels consists mainly of ethanol and biodiesel production. The global ethanol production and consumption in 2013 were dominated by the Unites States of America (USA) (57%) (REN21, 2014). The production of this ethanol however mainly used corn as feedstock (REN21, 2014). The production of biodiesel, which has a significant smaller share in the total biofuel production, is more spread across different countries. The EU-27 account for approximately 40% of the biodiesel production, whereas the USA accounts for 18% (REN21, 2014). Due to the Renewable Fuel Standard (RFS), which is a steadily increasing blending mandate for second generation biofuels (USDOE, 2008), the USA is projected to consume more than half of the worldwide biofuels in 2015. The RFS particularly mandates biofuels with lower GHG emissions than corn ethanol (USDOE, 2008) by requiring that 60.6 billion liters of lignocellulosic ethanol be consumed annually by 2022 (OECD, 2010). The blending requirements in the USA are expected to exceed the domestic biofuel supply, making import of biofuel necessary (OECD, 2010). At the same time pellet production is proliferating in recent years in the USA due to increased demand from European countries (Lamers, Junginger, Hamelinck, & Faaij, 2012). These countries are responding to renewable energy policies and financial incentives, which promote pellet consumption for electricity and heat generation (Qian & McDow, 2013).

The USA has a great potential to increase their bioenergy production. Smeets et al. (2007) have calculated[4] the technical bioenergy production potential for 2050 in North America to range between 39 and 204 EJ per year, depending on the production system. A large share (20-174 EJ yr^{-1}) of this potential comes from dedicated woody bioenergy crops on surplus agricultural land (Smeets et al., 2007). This project will explore different pathways to convert dedicated biomass into bioenergy.

In the global suitability map for rain-fed lignocellulosic feedstock produced by Fischer et al. (2009) the Southeastern USA region has among the highest global suitability for feedstock production. This is emphasized by the United States Department of Agriculture (USDA) who states that the biomass yield in this region is higher than in most other USA regions due to its robust growing season (USDA, 2010). It furthermore has the largest region of planted forests in the USA and, together with the pacific Northwest region, the most intensively managed forests (Vance, Maguire, & Zalesny Jr, 2010). Based on the feedstock yield and land availability in the region the USDA (2010) expects the Southeastern USA region to provide 49,8% of the USA's advanced biofuels by 2022. Over 80 million hectares of the region are used for timber products, and an additional 2 million hectares of idle farmland could potentially be used for energy crop production (Kline & Coleman, 2010). The paper manufacturing sector, which is one of the largest wood related sectors in this region, has decreased its demand for wood fiber substantially (Wear, Prestemon, Huggett, & Carter, 2011) due to an increased share of recycled material for paper production and increased capacity outside of the USA (Wear et al., 2011). The declining wood demand and the increasing biomass yields could allow for increased biomass production without land-use change (Jonker, Junginger, & Faaij, 2014). Moreover, the infrastructure currently already in place will facilitate the use of biomass feedstock from this region without high investment costs.

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[4] The technical bioenergy production potential is based on the combined potentials of dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth.

To be able to use energy crops in the most efficient manner for the production of bioenergy, the processes from growth all the way through conversion need to be considered. Gan and Smith (2011) described a bioenergy supply chain as the interrelated processes; growing, harvesting, transporting, processing, storing and conversion of biomass feedstock into different secondary energy carriers. They note that proper coordination of the production processes is of great importance, and decisions on development and deployment should therefore be based on the optimization of the complete chain. Of the above mentioned activities mainly growing, transporting and conversion have a strong influence on the costs and GHG emissions of bioenergy production. During the growing process biomass cultivation practices are applied resulting in a growth yield of the biomass. With higher growth yields, more biomass is available on less land, resulting in lower bioenergy production costs and GHG emissions (Stephen, Mabee, & Saddler, 2010). Noteably, an increase in plant size will reduce the equipment costs in the conversion process due to scaling factors[5], but the higher feedstock demand will increase the costs and emissions of the transport process. Wright and Brown (2007a) state that an optimal size for biorefineries exists, depending on the nature of the biomass and the applied conversion processes.

Since the reduction in GHG emissions is one of the main drivers of bioenergy consumption, the GHG emissions in bioenergy production is an important indicator (van der Hilst, 2012). Bioenergy production is however only economically feasible if the produced bioenergy is cost-competitive with fossil fuels. The costs and GHG emissions of bioenergy production are influenced by the different types of biomass used as feedstock, the selections in the handling and the mode of transport of biomass, and the processing technologies utilized for biomass to bioenergy conversion. Other important parameters in the supply chain are the biomass growth yield, transport distance, conversion efficiency and scale. Many studies look at bioenergy production, yet no study has compared the costs and GHG emissions of different viable conversion configurations for forestry biomass in the Southeastern USA region. Most of available literature focusses on only one process of the supply chain, on the supply chain of one single conversion technology or on the utilization of one type of feedstock. Furthermore, different studies use dissimilar assumptions and input data making it difficult to compare results. The Southeastern USA region provides a large potential to reduce GHG emissions through the production of bioenergy. Understanding how the costs and the GHG emissions in the production and consumption of different bioenergy types relate to the costs and GHG emissions in the fossil fuels which they can substitute is essential for maximization of energy production and GHG mitigation.

The development of the optimal bioenergy supply chain requires knowledge on all necessary processes in the supply chain as well as knowledge on how to improve these processes. Bottom-up analysis can raise an understanding of what the economic and GHG emission performance of bioenergy production will be, as well as how the performance is influenced by key parameters in the supply chain. It will also improve the understanding of how alterations in processes could influence future performance of bioenergy supply chains. This research will give an indication of the costs and GHG emissions involved in bioenergy conversion, and will aid in selecting biomass to bioenergy conversion configurations for the Southeastern USA region. For each configuration the GHG emissions reduction potential and the GHG emissions abatement cost will be calculated. This research will consider different feedstocks and conversion technologies which are described in literature as

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[5] The scale factor is an indication for the change in capital cost due to a change in plant scale (de Wit et al., 2010). The ratio between the capital cost of a new and old plant can be calculated by the ratio between the scale of the new and old plant raised to the power of the scale factor.

commercially viable, and all calculations will be performed for the year 2014. The comparison will be performed using the same type of costs, scale and region for all configurations.

The aim of this project is to **determine the potential economic performance and GHG emission intensity of state of the art biomass to bioenergy conversion configurations - using selected feedstock and conversion technologies- in the Southeast of the USA.**

In order to answer to the main research question the following sub-questions will be addressed:

I Which second generation biomass conversion configurations are currently viable in the Southeastern USA region based on feedstock availability and technological states of conversion technologies?

II What are the costs and GHG emissions of lignocellulosic biomass cultivation, harvesting and transport in the Southeast USA at the selected configuration scale?

III What are the costs and GHG emissions of industrial processing of biomass to bioenergy at the selected configuration scale?

IV How does the bioenergy produced by the different configurations compare to the fossil fuels which they can substitute?

V Which combination of conversion technology and biomass feedstock is currently most promising for bioenergy production?

In chapter 2 the different processes involved in the bioenergy supply chain will be described and a selection in viable conversion configurations will be made. In chapter 3 the methodology will elaborate on how the GHG emissions and costs involved in each processes of the conversion chain will be determined. Following this chapter 4 will discuss the key parameters and assumptions used for this research. The results of the costs and GHG emission calculations of the supply chain processes and the total supply chain are given in chapter 5. Finally, chapter 6 and 7 describe the discussion and conclusion of this research.

2. Supply chain description

The supply chain of bioenergy production can be divided into five processes: feedstock cultivation, harvesting, transport, pretreatment and storage, and conversion. Figure 1 depicts the structure of the supply chains and shows the interactions between processes. Pretreatment and intermediate storage can be done separately from the processing factory. This research will however assume that both processes are performed at the same location to limit the number of different configurations. The combined pretreatment and conversion will be named processing from here on. In the rest of this chapter each of the processes will be explained.

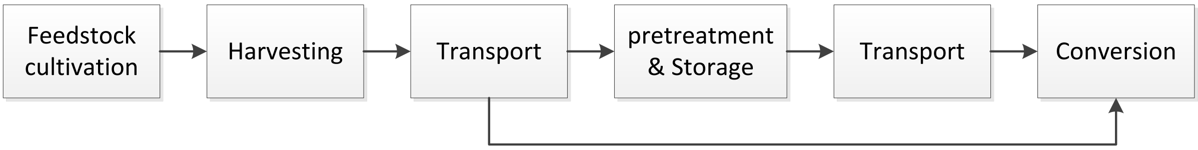

Figure 1 General process layout of a bioenergy supply chain.

2.1 Feedstock cultivation

Different types of forestry biomass can be used for bioenergy production. Junginger, Lamers and Wicke (2014) have described a division, of bioenergy feedstock from forestry, into ‘main product’, ‘co-product’ and ‘residue’. The group **main product** concerns woody biomass from plantations with wood which is used solely or mainly for bioenergy production. Forestry **co-product** and **forestry residue** are biomass from land which is not used primarily for bioenergy feedstock production, but could be used for bioenergy production anyways. Forestry co-product however has potential alternative uses than only bioenergy production, while forestry residue has no alternative uses.

Another classification can be made based on the supply sector, dividing it into feedstock from agricultural residues, forestry residues, dedicated energy crops, industry, parks and gardens, wastes and others (Tumuluru et al., 2011). In a report by Union of Concerned Scientists (2012), it is estimated that the biggest potential of biomass feedstock in 2030 in the USA will come from forestry residues, agricultural residues and dedicated energy crops. Kimbell et al. (2009) however note that the extra steps, which are necessary to transport agricultural residue to the processing factory, might have a negative effect on the costs and the GHG emissions of the final products.

While dedicated forestry concerns roundwood from fields used solely for bioenergy production, forestry residue concerns left on-site wood residues after roundwood is harvested for other purposes (Galik, Abt, & Wu, 2009). Not all biomass from forests can be used by the traditional wood sectors, which leads to wood being left behind. Small trees and damaged forests currently remain unused forming a potential source for bioenergy (Worldwatch Institute, 2006). A share of this wood should however remain in the forests for habitat conservation and carbon storage (Worldwatch Institute, 2006). White (2009) mentions that there is some evidence that the removal of harvest residues can reduce the soil nutrients, which may affect future growth yield. The biomass from forestry residue is likely to have lower costs for cultivation, but higher costs for harvesting and transport due to a lower yield. Dedicated bioenergy crops will involve higher costs for cultivation, but the higher biomass yield will lead to lower costs for harvesting and transport. Dedicated biomass, however has the additional benefit that genetic modifications can be applied resulting in biomass with more desirable characteristics (Potumarthi, O’Donovan, & Sharma, 2014; Sannigrahi, Ragauskas, & Tuskan, 2010; Worldwatch Institute, 2006).

In the scenario’s modelled for this research, only the feedstock group main product will be considered. Since it is too time consuming for this research to consider the availability of residues, to allocate a part of the costs and GHG emissions of the forestry practices to the residue, and to assess the effect of the removal of harvest residues on the reduction of soil nutrients this feedstock group will be left out of scope. It is however important to note that configurations using this feedstock group may perform equally or even better than the selected configurations.

Another classification of biomass feedstock can be made based on the type of biomass, dividing it into softwood and hardwood. Kline and Coleman (2010) have looked at the potential for different types of hardwood tree species to be used as biomass feedstock in the Southeastern United States. They state that, even though the research focused on hardwood, the Southeastern forestry community currently considers loblolly pine to be the best feedstock for commercial bioenergy production in the region, based on conducted interviews. Since loblolly pine has widely been grown in the Southeastern USA region for fiber and timber, the pine industry has developed high pine growth rates at low production costs (Kline & Coleman, 2010). In Georgia Loblolly-shortleaf pine is the main type of softwood on timberland. Of the timberland in the Georgia area, 18% is planted Loblolly-shortleaf pine and 13% is natural Loblolly-shortleaf pine (Harper, 2012) whereas the total share of timberland occupied by hardwood in Georgia is 53% (Harper, 2012).

In a scenario in which dedicated forestry biomass is utilized, a management intensity for the land should be determined. Land management is the general term which comprises all activities to improve biomass growth, including irrigation, fertilizers and pesticide use (Edenhofer et al., 2012). It has been extensively reported that improvements in land management can lead to increasing yields (Rauscher & Johnsen, 2004). This is crucial for future large-scale deployment of biomass for bioenergy since it can reduce the demand for land (Edenhofer et al., 2012) and will ensure long-term sustainability (Food and Agriculture Organization, 2008). A lower demand for land will subsequently lead to shorter transport distances. Biomass productivity has increased over the last 50 years through plant breeding and improved land management practices (Edenhofer et al., 2012). In an article by Siry on the status and trends of forest management practices between 2000 and 2020 in the Southern USA, increased management intensities are projected on all land for planted pine and hardwood (Siry, 2002).

2.2 Harvesting

When the biomass has reached the optimal size to be used as feedstock, machines are used for harvesting, and transport preparation. Typical machines necessary for whole stem biomass harvesting are feller-bunchers, forwarders and skidders (Spinelli, Ward, & Owende, 2009). Kluender et al. (1997) show that the stem size of trees and the average distance between trees have a large influence on the equipment productivity. For this research it is however assumed that the productivity of selected equipment is equal for both feedstock types.

2.3 Transport

Different modes of transport can be used to move biomass from the land to the pretreatment facility or processing factory. Generally biomass transport is performed by truck, train or boat. Multiple studies have shown that trucks are considered the best transport mode for transport distances below 100 km (Hamelinck, Suurs, & Faaij, 2005; Ruiz, Juárez, Morales, Muñoz, & Mendívil, 2013). Since this research will focus on transport over short distances, trucks are the only considered transport mode.

The transport of biomass by truck requires an infrastructure of roads from the forest land to the processing factory and possibly to intermediate pretreatment facilities. It should be considered if the available infrastructure is sufficient, or if it should be expanded.

2.4 Pretreatment

Applying pretreatment to biomass feedstock has several purposes. First, many conversion technologies require a quality level and homogeneity of the used biomass feedstock which is often not met by untreated biomass (IEA Bioenergy, 2009). Secondly, pretreatment can be used to make biomass vulnerable to conversion processes (Garver & Liu, 2014). Ultimately, pretreatment can decrease the costs, and increase the efficiency and reliability, of the supply chain (IEA Bioenergy, 2009; Richard, 2010).

Different pretreatment options exist which use or exploit thermal, mechanical or chemical mechanisms in order to break down the strong chemical structures in biomass (Garver & Liu, 2014). For this research, however, only biomass drying and size reduction will be assumed.

Biomass pretreatment can be applied at once in the processing factory, or at other locations closer to the forest land. Intermediate pretreatment will likely increase the total transport, but the transport from the pretreatment facility to the conversion plant will be able to carry more useful biomass per load. It should be noted that the costs for loading and unloading will increase if intermediate pretreatment facilities are applied. Due to time constraints, this research will only consider pretreatment at the same location as the conversion facility.

2.5 Conversion

Biomass is converted into different energy carriers by different conversion technologies. Figure 2 shows the considered technologies for this investigation, and the final products that they produce. Each conversion technology contains a chain of processes which follow each other in order to convert the biomass into more useful biofuels. In addition to the final products, the conversion technologies may also produce by-products (e.g. energy and chemicals). The conversion technologies will now briefly be discussed.

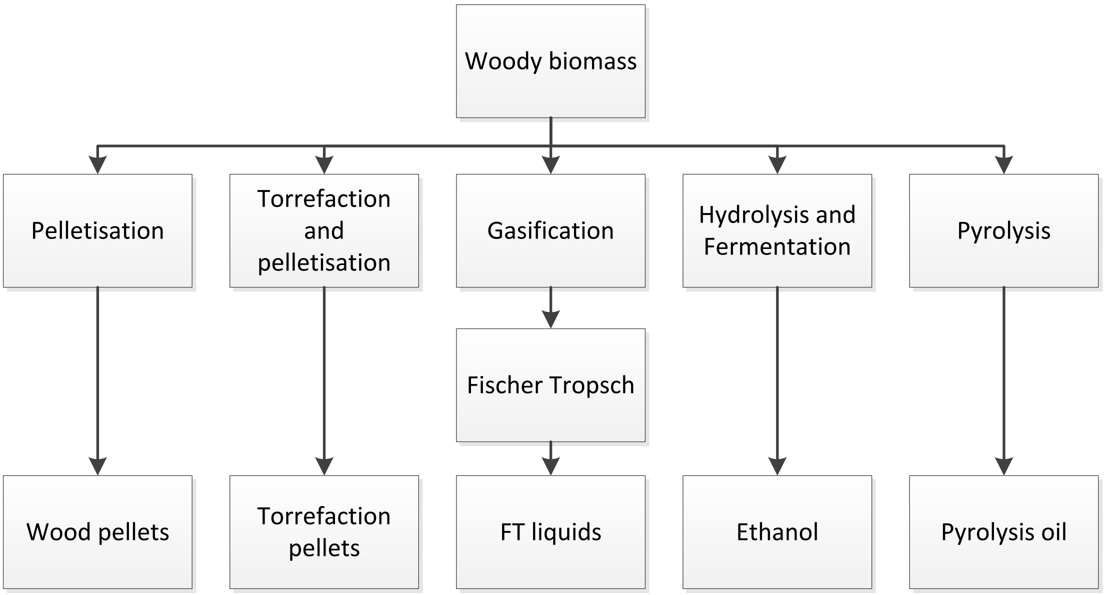

Figure 2 Biomass to bioenergy conversion technologies and produced final energy carriers.

2.5.1 Pelletizing

Pelletization concerns the compressing of biomass into pellets with a uniform size, moisture and heat content (Gerssen-Gondelach, Saygin, Wicke, Patel, & Faaij, 2014). Pellets have an higher energy density than biomass making them easier to transport, store and combust (Wolf, Vidlund, & Andersson, 2006). Pellets have become a common type of fuel in both households and industry (IEA Bioenergy, 2009).

The processes involved in the conversion of biomass into pellets are: size reduction, drying, pelletizing and cooling (Bergman & Veringa, 2005; Fantozzi & Buratti, 2010; Mobini, Sowlati, & Sokhansanj, 2013; Qian & McDow, 2013) (see Figure 3).

Figure 3 Basic process structure of pelletizing.

The global production of pellets in 2013 reached 23.6 million metric tonnes, making it one of the main types of solid biofuel (REN21, 2014). This production has mainly takes place in the EU (50%) and North America (33%) (REN21, 2014). In this research, the production of pellets which can be used for co-firing in existing coal-fired power stations is assumed. By co-firing pellets a part of the coal is substituted by pellets (Bergman & Veringa, 2005).

2.5.2 Torrefaction and pelletizing

Torrefaction is a technology which applies thermal upgrading to biomass in order to obtain a more homogeneous solid biofuel (Batidzirai et al., 2013). During torrefaction approximately 30% of the original mass in converted into torrefaction gases, which contain only 10% of the original energy content. The remaining 70% of the mass is converted into solid torrefied biomass with considerable energy densification (Bergman & Veringa, 2005; Uslu, Faaij, & Bergman, 2008). The obtained biofuel can be densified by pelletization resulting in torrefied pellets (TOPs) (Gerssen-Gondelach et al., 2014), which have properties similar to coal, giving it the potential to directly replace coal (Batidzirai et al., 2013). One of the advantages of TOPs over pellets is that TOPs are hydrophobic, meaning that it will not absorb moist during transport and storage (IEA Bioenergy, 2009). An integrated torrefaction plant generally involves size reduction, drying, torrefaction, size reduction, cooling, pelletization and cooling (Batidzirai et al., 2013; Bergman & Veringa, 2005) (see Figure 4).

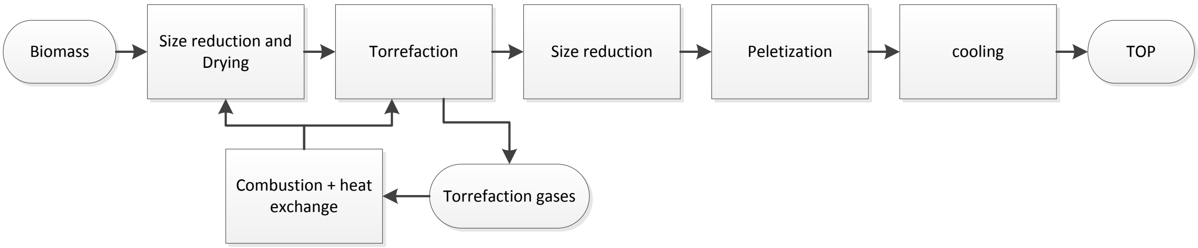

Figure 4 Basic process structure of combined torrefaction and pelletization.

The global annual production of torrefied pellets still remained below 200,000 tonnes in 2013 (REN21, 2014). Similar to the pelleting conversion technology, the TOP process conversion technology produces solid bioenergy which can be co-fired in existing coal-fired power stations.

2.5.3 Gasification and Fischer-Tropsch synthesis

During gasification biomass is heated at a high temperature and pressure with a low amount of oxygen in a gasifier resulting in a mixture of gasses (Gerssen-Gondelach et al., 2014; Meerman, 2012). Gasification can be done at different temperatures leading to different final products. While product gas is obtained at a gasification at 900-1000 °C, syngas can be obtained by gasification at temperatures above 1500 °C (Gerssen-Gondelach et al., 2014). Even though the production of product gas is often preferred because of the higher conversion efficiency, syngas is more convenient for biofuel production due to its higher H_2 and CO concentrations (Gerssen-Gondelach et al., 2014). This research will therefore only consider gasification for syngas production. The produced syngas can be used for the production of electricity, transport fuels and other chemicals (Meerman, 2012).

One of the technologies which can be used to convert syngas into liquid transport fuels is Fischer-Tropsch (FT) synthesis (Larson, Jin, & Celik, 2005; Tijmensen, Faaij, Hamelinck, & Van Hardeveld, 2002). FT synthesis is becoming more popular due to changes in environmental demands, increased 'stranded' gas and technological developments (Tijmensen et al., 2002). Furthermore, diesel produced by FT is very similar to the fossil fuel diesel allowing it to directly replace conventional diesel and to make use of the conventional diesel infrastructure (Meerman, 2012).

In order to use syngas for FT synthesis, the syngas needs to be cleaned and processed. The gas processing involves methane reforming, a shift reaction and CO_2 removal in order to reduce inert gases (Tijmensen et al., 2002). After gas processing the FT synthesis produces hydrocarbons from the H_2 and CO in the syngas (Klerk, 2011). The conversion of syngas by FT synthesis results in both liquid fuel and off-gas, which is unconverted syngas. In a once-through FT synthesis the off-gas is used for energy production or as heat elsewhere in the system, while a full conversion FT synthesis recycles the off-gas to increase the production of FT liquids (Hamelinck, Faaij, den Uil, & Boerrigter, 2004; Larson et al., 2005; Tijmensen et al., 2002).

While Gasification and Fischer-Tropsch can be performed separately it has advantages to perform both technologies at one single facility. Kreutz et al. (2008) show that excess heat is produced during the FT process, while the air separation unit and the gasification process consume energy. By applying a power generator and a heat recovery generator after the FT synthesis the factory will be able to produce electricity for own consumption, and to re-use heat for other processes (Swanson, Satrio, Brown, Platon, & Hsu, 2010a)

The general processes involved in gasification are size reduction, drying, gasification, gas cleanup, acid gas removal, and FT synthesis (Kreutz, Larson, Liu, & Williams, 2008; Meerman, 2012; Swanson et al., 2010a). (See Figure 5).

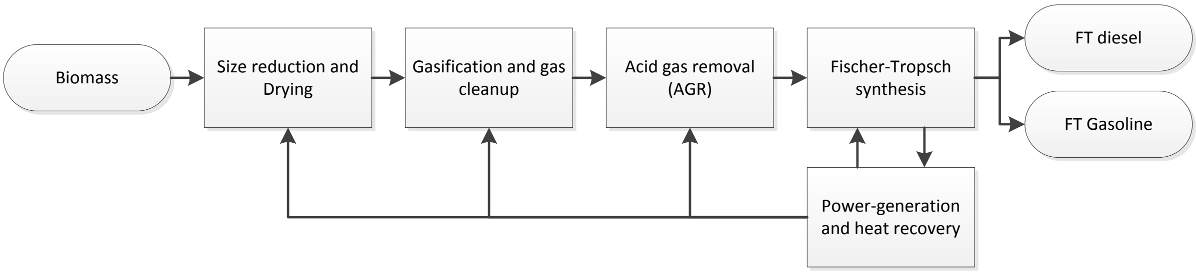

Figure 5 Basic process structure of combined gasification and FT synthesis.

The production of syngas in 2010 mainly took place in Asia/Australia (37%) and in Africa/Middle east (36%) (NETL, 2010). The production of syngas in North America was relatively low (10%), but has been expected to significantly increase. Of the global total planned capacity growth from 2010 up to 2016, 63% would be constructed in North America (NETL, 2010). It should however be noted that the used feedstock for syngas production mainly concerned the fossil fuels coal, petroleum and gas.

2.5.4 Hydrolysis and Fermentation

Fermentation is a conversion technology which uses sugars in feedstock to produce ethanol. Since lignocellulosic feedstock does not contain sugars which are readily available this feedstock requires the conversion of carbohydrates into sugars first (Demirbas, 2005; IEA Bioenergy, 2009). The necessary pretreatment process (e.g. hydrolysis or steam explosion) breaks up the major components of lignocellulosic biomass to make the biomass vulnerable for further treatment (Demirbas, 2005; Gerssen-Gondelach et al., 2014). Subsequently hydrolysis converts the cellulose and hemicelluloses in the biomass into sugar, which can then be converted to ethanol by fermentation (Demirbas, 2005; Gerssen-Gondelach et al., 2014). The chemical composition of the used feedstock is therefore an important determinant for the theoretical ethanol yield of fermentation. Lignin, which is one of the structural materials in biomass, cannot be converted into fermentable sugars, but it can however be used for energy generation (Cherubini, 2010; Humbird et al., 2011b). The ethanol produced by hydrolysis and fermentation can substitute, or be blended with, gasoline (Gonzalez, Treasure, Phillips, Jameel, & Saloni, 2011).

In the conversion of biomass by fermentation size reduction, pretreatment and hydrolysis to obtain fermentable sugars, fermentation to convert sugars into ethanol, and ethanol purification by distillation are used (Anwar, Gulfraz, & Irshad, 2014; Asgher, Shahid, Kamal, & Iqbal, 2014; Demirbas, 2005; Hamelinck, Van Hooijdonk, & Faaij, 2005). (See Figure 6).

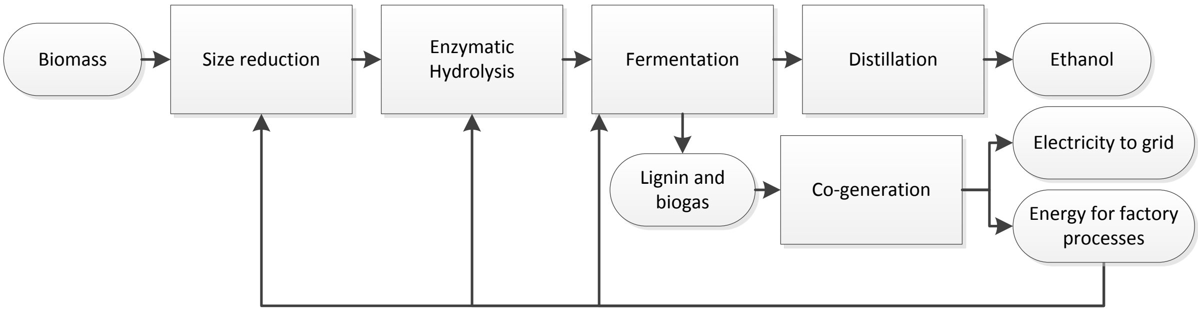

Figure 6 Basic process structure of fermentation.

2.5.5 Pyrolysis oil

Pyrolysis concerns the thermal decomposition of biomass into liquid bio-oil, syngas and charcoal (IEA Bioenergy, 2009). On average pyrolysis results in 70 wt% bio-oil,10-15 wt% syngas, and the remaining charcoal (Ringer, Putsche, & Scahill, 2006). However, different types of pyrolysis processes exist which lead to different compositions of biofuels. Pyrolysis with a high production of bio-oil is given most attention, since this fuel is cheaper to handle, transport and store than charcoal (IEA Bioenergy, 2009). The applications of bio-oil are limited due to its properties, which make it incompatible with standard petroleum fuels (Carpenter, Westover, Czernik, & Jablonski, 2014). Bio-oil can however be upgraded to more usable fuels and chemicals (Carpenter et al., 2014). This research will consider all bio-oil to be upgraded to gasoline and diesel blendstock (Jones, Meyer, Snowden-Swan, & Padmaperuma, 2013).

The production of bio-oil by pyrolysis involves the following processes: size reduction and drying, pyrolysis, charcoal combustion, product recovery and steam generation (Ringer et al., 2006) (see Figure 7).

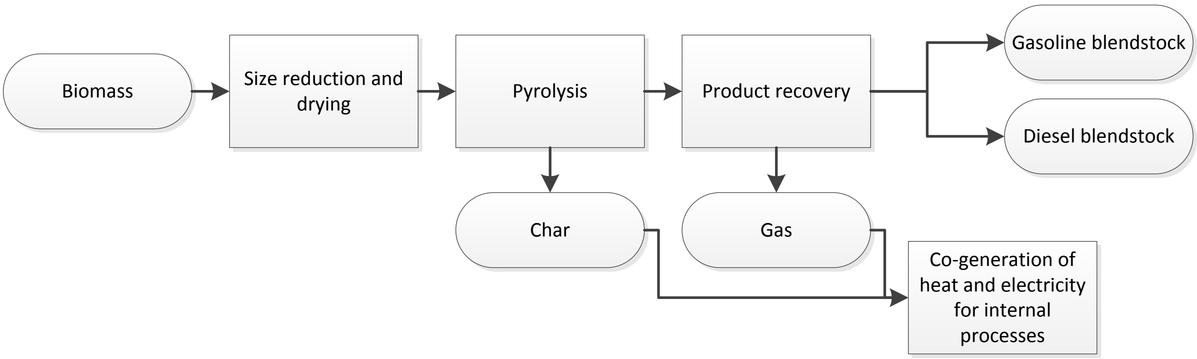

Figure 7 Basic process structure of pyrolysis.

3. Methodology

The goal of this research is to compare different bioenergy supply chains for the Southeastern USA region, to their reference fossil fuel, based on their economic performance and their GHG emissions. This research focusses on all costs and GHG emissions involved in the complete bioenergy supply chain. The system boundary for this research will encompass biomass cultivation, harvesting, transport of biomass, and the conversion of biomass into bioenergy carriers. The transport and distribution of bioenergy to the end user is not considered in this research since this would require assumptions for the geographical location of the bioenergy consumers. Two types of biomass feedstock and five conversion technologies are considered, resulting in 10 different configurations.

The total costs and emissions of the supply chain are calculated by adding the costs and emissions of the different supply chain processes together. The total costs and emissions will be calculated using the following equations:

$$SCC = \frac{CC + HC + TC}{\mathrm{R}} + PC$$

Equation 3.1

SCC	Total supply chain costs	$\$/\mathrm{GJ}_{\mathrm{bioenergy}}$
CC	Cultivation costs	\$/tonne
HC	Harvesting costs	\$/tonne
TC	Transport costs	\$/tonne
PC	Processing costs	$\$/\mathrm{GJ}_{\mathrm{bioenergy}}$
R	Conversion ratio	$\mathrm{GJ}_{\mathrm{bioenergy}}/\mathrm{tonne}$

$$SCE = \frac{CE + HE + TE}{\mathrm{R}} + PE$$

Equation 3.2

SCE	Total supply chain emissions	$\mathrm{CO_2eq}/\mathrm{GJ}_{\mathrm{bioenergy}}$
CE	Cultivation emissions	$\mathrm{CO_2eq}/\mathrm{tonne}$
HE	Harvesting emissions	$\mathrm{CO_2eq}/\mathrm{tonne}$
TE	Transport emissions	$\mathrm{CO_2eq}/\mathrm{tonne}$
PE	Processing emissions	$\mathrm{CO_2eq}/\mathrm{GJ}_{\mathrm{bioenergy}}$
R	Conversion ratio	$\mathrm{GJ}_{\mathrm{bioenergy}}/\mathrm{tonne}$

The costs and GHG emissions of produced bioenergy will be compared to a reference fossil energy and to each other. Bird et al. (2011) emphasize that care should be taken in that the comparison is valid, to prevent the comparison between ‘apples and oranges’. Therefore, the produced bioenergy types will be compared to the fossil fuel type that is most likely to be replaced.

The chains considered in this research produce different types of energy carriers, namely solid, liquid and gaseous biofuels. Therefore, the comparison will be made based on the cost per GJ bioenergy produced ($\$/GJ_{Bioenergy}$), and the GHG emissions per GJ bioenergy produced ($CO_2eq/GJ_{Bioenergy}$).

All costs in this research will be transformed to $\$_{2014}$. The Consumer Price Index (CPI) will be used which is made available by the Bureau of Labor Statistics and is a measure for the change in prices paid by consumers for a market basket of goods and services (BLS, 2015).

In the chapters 3.1 to 3.4 the calculation methods for the costs and emissions of the different processes in the supply chain are given. Chapter 3.5 shows how all costs and emissions of the supply chain are added together for the selected scale. Thereafter, the methods for the sensitivity analysis are discussed.

3.1 Costs and emissions of biomass cultivation

Literature review, corporate information and expert opinion will be used to determine all costs involved in biomass cultivation. Most values are geographically heterogeneous and will therefore be determined specifically for the Southeastern USA region. If no data can be found for this region values will be assumed and motivated based on available data on other regions or crops.

The economic analysis of the biomass cultivation will be performed using a Net Present Value (NPV) approach. This is necessary since the costs and benefits of biomass production do not occur simultaneously and thus have to be compared in different years. An equation described by van der Hilst (2012) will be used in order to compare the cultivation costs of the different feedstock types. This equation discounts all costs in the feedstock cultivation phase, and provides the cultivation costs per tonne for each feedstock (see Equation 3.3).

$$CC = \left(\sum_{y=1}^{y=x} \frac{\sum_{n=1}^{N}(I_{ny} * C_{ny}) + \sum_{m=1}^{M}(J_{my} * C_{my} * Y_y)}{(1+a)^y} \right) / \left(\sum_{x=1}^{y=x} \frac{Y_y}{(1+a)^y} \right)$$

Equation 3.3

CC	Discounted cultivation costs	\$/tonne
I_{ny}	Occurrence cost item per ha n	#
C_{ny}	Cost of cost item n	\$/ha
J_{my}	Occurrence cost item per tonne m	#
C_{my}	Cost of cost item m	\$/tonne
Y_y	Growth yield of biomass in year y	Tonne/ha
a	Discount rate	%
y	Felling frequency	year

In this equation the costs per hectare concern the costs for land lease and for several of the practices in land management. The costs per tonne concern the costs of other biomass management practices. The cost for land lease is the annual price per hectare for the used land and it is assumed equal for both biomass types, and independent of the selected scale. This means that a high demand for land will not increase the price per hectare. The costs for input in biomass management concern costs per hectare for land preparation and pesticides, and costs per tonne for fertilizers (van der Hilst, 2012). The felling frequency of forestry biomass is important since it determines when the biomass can be used for bioenergy production. The felling frequency for both biomass types is obtained from literature for the Southeastern USA region.

While the costs for biomass cultivation are discounted over time, this is not necessary for the GHG emissions of biomass cultivation, where the value of a GHG emission at a moment in time is equal to the value of the same emission at a future moment in time. The GHG emissions of the cultivation process are therefore calculated by summing all emissions generated during the cultivation of one tonne biomass (Equation 3.4). The emissions of the land management are based on the used fertilizers, herbicides and equipment fuel consumption. The emissions from land use change are not considered in this research.

$$CE = \sum K_n + \left(\frac{\sum L_m}{y_h}\right)$$

Equation 3.4

CE	Emissions from cultivation	CO_2eq/tonne
K_n	Emission of emission item n	CO_2eq/tonne
L_m	Emission of emission item m	CO_2eq/ha
y_h	Harvesting yield	tonne/ha

3.2 Costs and emissions of harvesting

Literature review as well as corporate information and expert opinion will be used to determine the capacities, load factors, utilization costs and fixed costs of common practice harvesting equipment. In order to calculate the total harvesting costs, all costs are transformed into costs per hectare. The costs per tonne are transformed by multiplying the costs by the harvesting yield.

In the costs for harvesting a distinction is made in the field operational costs and in the fixed costs of harvesting equipment. The operational costs include variable machinery costs, labor and fuel costs, and can be divided into land size dependent costs ($/hectare), and biomass weight dependent costs ($/tonne). The fixed costs include equipment depreciation, insurance and taxes, and are calculated as the annual costs per machine. In order to facilitate the calculations for the harvesting costs, the fixed costs for capital are integrated in the costs per hectare and the costs per tonne (Equation 3.5). At a small scale, integrating the capital costs in the costs per hectare and the costs per tonne could lead to an underestimate in the harvesting costs since the amount of machines should be integer, likely resulting in a small overcapacity. At the selected scale, however, this overcapacity is considered negligible.

$$HC = \sum_{a=1}^{A} (I_a * C_a) + \frac{\sum_{b=1}^{B} (I_b * C_b)}{y_h}$$

Equation 3.5

HC	Harvesting costs	$/tonne
I_a	occurrence cost item per tonne a	#
C_a	cost of cost item a	$/tonne
I_b	occurrence cost item per hectare b	#
C_b	cost of cost item b	$/ha
y_h	Harvesting yield	tonne/ha

The GHG emissions in the harvesting process come from the fuel used by harvesting equipment. To calculate the emissions per tonne harvested the rated fuel use of all necessary equipment is multiplied by the fuel specific emission factor (Equation 3.6).

$$HE = \sum \mathrm{FC} * \mathrm{EF}$$

Equation 3.6

HE	Emissions from harvesting	CO_2eq/tonne
FC	Fuel consumption	L/tonne
EF	fuel specific emission factor	CO_2eq/L

3.3 Costs and emissions of transport

Literature, corporate information and expert opinion will be used to find the key variable values for biomass feedstock transport. The costs in biomass transport are divided into operational costs and fixed truck costs. In biomass transport the operational costs concern distance fixed costs (DFC) for loading and unloading ($/tonne) and distance variable costs (DVC) for road transport ($/tonne-km). The fixed costs per truck include the costs for equipment purchase, insurance and taxes. Similar to the method described in 3.2 the fixed truck costs are incorporated into the operational costs for transport. The transport costs per tonne are calculated using Equation 3.7. In the equation the costs per loading are costs that are independent of the average transport distance. The specific costs of loading and unloading are divided by the mass per load to obtain the loading costs per tonne. For the calculations of the costs of transport the empty return travel of trucks has to be accounted for as well using the ratio ‘r’. In order to ease the data collection and calculations in this research it is assumed that the travel duration and fuel consumption of the return travel are both 30% lower than the loaded truck travel. The round trip distance can then be calculated by multiplying the average transport distance by a factor 1.7.

$$TC = \left(\frac{DFC}{L_{av}}\right) + DVC * D * r$$

Equation 3.7

TC	Transport costs	$/tonne
DFC	Costs per loading	$/load
L_{av}	Average weight per loading	tonne/load
DVC	Costs of road transport	$/tonnekm
D	Average transport distance	Km
r	Ratio round trip costs : loaded trip costs	-

The average transport distance is an important factor in the costs and emissions of the transport process. In order to calculate this, an assumptions needs to be made for the geographical distribution of land and the present infrastructure. This research assumes that the used land is circular in shape, and that the conversion plant is located in the center of this circle. Furthermore, an optimal geographical distribution is assumed such that all land near the conversion plant can be used for biomass cultivation. While the theoretical average transport distance within a circle is 2/3 times the radius, the actual average transport distance is larger due to the suboptimal nature of the road network, which prevents straight-line transport. Wright et al. (2007) described the ratio of the actual average distance to the theoretical average distance as a ‘tortuosity factor’, ranging between 1.2 for developed agricultural regions and 3.0 for less developed agricultural regions. In Equation 3.8, which calculates this transport distance, the land size is entered in km^2, using the ha to km^2 conversion factor of 0.01.

$$D = \tau * \frac{2}{3} * \sqrt{A/\pi}$$

Equation 3.8

D	Average transport distance	km
τ	Tortuosity factor	-
A	Land size	km^2

In this equation land size is defined, using the annual biomass demand, the growth yield of biomass, and the fraction of land that can be used for biomass production (Equation 3.9). In this equation the fraction 'f' accounts for all land that cannot be used for biomass (e.g. roads).

$$\mathrm{A} = \frac{\mathrm{Q/Y}}{f}$$

Equation 3.9

A	Land size	ha
Q	Annual biomass demand	Tonne/year
Y	Growth yield	Tonne/(ha*year)
f	Fraction of land usable for biomass production	%

The GHG emissions of the transport process are calculated by multiplying the fuel consumption of trucks per tonne transported by the fuel specific emission factor. These calculations include the emissions from the empty return travel of trucks by using the same ratio 'r' as in Equation 3.7.

$$TE = \mathrm{FC} * \mathrm{EF} * \mathrm{r}$$

Equation 3.10

TE	Emissions from transport	CO_2eq/tonne
FC	Fuel consumption	L/tonne
EF	fuel specific emission factor	CO_2eq/L
r	Ratio round trip emissions : loaded trip emissions	-

3.4 Costs and emissions of processing

The costs in biomass processing involve capital costs and operating expenses. The capital costs for processing include the investments in equipment for pretreatment and conversion, installation costs of the equipment, and additional direct and indirect costs that are calculated as a percentage of the installed equipment costs. The operating expenses include all annual costs made during operation in labor, maintenance, insurance and taxes, and material and energy input. All costs of biomass processing will be calculated per produced GJ bioenergy using Equation 3.11.

$$PC = \frac{EAC + \sum \mathrm{C}_o - \sum B}{E}$$

Equation 3.11

PC	Processing costs	$\$/GJ_{bioenergy}$
EAC	Equivalent annual costs of conversion plant capital	\$/year
C_o	Operating expenses	\$/year
B	Benefit of co-product sales	\$/year
E	Annual bioenergy production	$GJ_{bioenergy}$/year

The main focus in this research will be on the production of solid, liquid and gaseous bioenergy. Some technologies however produce by-products, which should be taken into account. The price of produced by-products that can be sold will be added to the operating expenses as a benefit.

Due to different conversion efficiencies of the conversion technologies de amount of bioenergy produced by each configuration will differ. The bioenergy production per tonne biomass is dependent on the heating value and the chemical composition of the used biomass, and on the conversion technology. The conversion efficiencies used for this research are based on literature and expert opinion. The data on the chemical composition of the feedstock is obtained from the Phyllis-database[6].

The capital costs for a conversion facility are calculated as a one-time investment cost, whereas the operational costs are annual costs. To combine these two into a single value the capital costs will be transformed into annual costs. The equivalent annual cost (EAC) approach in Equation 3.12, which is deduced from the NPV equation, is used to transform the investment costs.

$$EAC = I/\left(\frac{1-(1+a)^{-y_e}}{a}\right)$$

Equation 3.12

EAC	Equivalent annual cost	\$/year
I	Total capital investment	\$
a	Discount rate conversion plant	%
y_e	Lifetime of equipment	year

In the EAC approach, the NPV of capital is divided by an annuity factor, resulting in a constant annual cost over the whole lifetime of the plant. Since the NPV in the installation year is equal to the total capital investment (TCI), the EAC can be calculated by dividing the investment cost by the annuity factor. For this research the lifetime of all equipment in a factory is assumed the same. The discount rate used in the EAC equation is a discount rate for renewable technologies, and is therefore not the same discount rate as used for the cultivation costs.

A standard scale will be used for each configuration concerning the biomass capacity of the conversion plant. Based on literature the plant capacity for all configurations has been set to 2000 dry metric tonne/day, which is in line with research performed by Dutta et al. (2011), Humbird et al. (2011) and Kazi et al. (2010). By using an equal biomass requirement for all configurations, a fair comparison can be made between the configurations. The parameters in processing are assumed to be geographically homogeneous. Therefore, these values do not need to be identified specifically for the Southeastern USA region.

For each conversion technology a base size will be determined together with its specific capacity, investment cost and operational costs based on literature. The capital costs of equipment are dependent on the scale of the selected configuration. Using the costs of a base size configuration, and equipment specific scaling factors, the investment costs for any size processing factory can be calculated (Equation 3.13).

$$Cost_2 = Cost_1 * (\frac{scale_2}{scale_1})^R$$

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[6] The Phyllis-database which is managed by ECN is available online on https://www.ecn.nl/phyllis2/

Equation 3.13

In equation 3.13, $cost_1$ and $scale_1$ concern the price and scale of the base size equipment, $cost_2$ concerns the price of the desired equipment size $scale_2$, and R is the equipment specific scaling factor. Some technologies have poor scale-up characteristics, making it difficult to identify the potential to upscale each component of a conversion technology (Bergman & Veringa, 2005). If the increase of a plant scale requires the use of multiple units of one component, due to a maximum size of the component, a multiplication exponent of 0.9 can be used instead of the equipment specific scaling factor (Kreutz et al., 2008; Meerman, 2012; Tijmensen et al., 2002). This exponent accounts for the possible sharing of auxiliary equipment and lower installation costs. For some technologies however the use of a multiple of one component makes it appear like the component cannot be up-scaled, while in fact it is sometimes desired to have a multiple of the component to ensure a continuous flow of materials within the production process. Andersson et al. (2006) recommend using a scaling factor of 0.7 for the overall equipment costs for a process if only a part of the equipment necessary for the process involve several parallel units.

While Equation 3.13 can be used for equipment costs this is not always the case for the operational costs. If literature shows that a specific scaling factor can be used for an operational cost, this factor will be used to calculate the operational cost at the new processing factory scale. However if this specific information is not available this research will determine what reasonable operational costs are at the selected factory scale. While some expenses are likely to have a similar scaling factor as the capital costs, other expenses are expected to increase linearly with an increase in configuration scale.

The calculations for all conversion technology economics in this research are based on the “nth” plant assumption. This assumption means that several plants using the same specific technology are already operating, and that costs of risk financing are thus not included (Phillips et al., 2007).

The GHG emissions from biomass pretreatment and processing are calculated by adding the emissions of all input materials and required energy together. If the configuration produces salable by-products, the average GHG emissions of producing the co-products elsewhere will be deducted from the emissions of the supply chain (equation 3.14). The biogenic emissions in biomass to bioenergy conversion are not considered in this research.

$$PE = \mathrm{ME} - \mathrm{SE}$$

Equation 3.14

PE	Emissions from processing	$CO_2eq/GJ_{bioenergy}$
ME	Emissions of input materials and energy	$CO_2eq/GJ_{bioenergy}$
SE	Emissions in producing co-products elsewhere	$CO_2eq/GJ_{bioenergy}$

3.5 Total costs and emissions of the supply chain

The total costs and emissions in bioenergy production of the different configurations are calculated using Equations 3.1 and 3.2. The costs and emissions of the cultivation, harvesting and transport processes are calculated per tonne biomass as stated in chapters 3.1-3.3. In order to transform these values into costs and emissions per produced GJ bioenergy, the values are divided by the conversion efficiency of the applied conversion technology.

3.6 Comparison with fossil fuel costs and emissions

The costs and emissions of the bioenergy from all configurations will be compared to the costs and emissions in the production and use of the fossil fuels which they can potentially replace. The costs used for the reference fossil fuels concern the costs for crude oil and for refining, and the GHG emissions of the reference fuels concern the GHG emission in the refining and the consumption of these fuels. The costs and emissions of pellets and TOPs will be compared to the reference fossil fuel Bituminous coal, which is commonly used as reference coal (Meerman, 2012). The reference fossil fuel for ethanol and gasoline blendstock is gasoline, and the reference for biodiesel is diesel (Hoefnagels, Smeets, & Faaij, 2010). The bioenergy produced by the FT and pyrolysis technologies is a mix of gasoline and diesel. The produced bioenergy will therefore be compared to a mix of the fossil fuels gasoline and diesel, based on the energy share of both components. Since the energy density of bioenergy is not necessarily the same as the energy density of the selected reference fossil fuel (Gonzalez et al., 2011), the comparison will be performed based on the costs and GHG emissions per GJ energy.

The transport of fossil fuels after refining, and of bioenergy after conversion, is not taken into consideration in this research. Since it is difficult to find the costs of gasoline and diesel production, the average 2014 fossil fuel retail prices will be multiplied by a percentage found in literature to obtain both the crude oil costs and the refining costs. By using this method the costs for distribution, marketing and taxes will not be included in the production costs.

The emissions of the reference fossil fuel will be calculated using the emission factors of the fossil fuels, and the fuel specific energy requirement for energy (ERE) which shows how much MJ primary energy is necessary to deliver 1 MJ energy. The ERE accounts for indirect energy requirements for extraction, transport, storage and refinery of delivered fuels (Blok, 2007). Since the transport of bioenergy after conversion is not taken into account in this research the used ERE values will be adjusted to exclude the energy used for fossil fuel transport.

3.7 Sensitivity analysis

A sensitivity analysis is used to assess the effect of the key parameters and uncertain parameters on the final results. The analysis will be performed by applying a range to the initial value of each of the parameters. This gives an indication of the influence of these processes on the performance of their final products. The range for each parameter is selected based on parameter values found in literature. If no indication for a range can be found, the range is selected between 80% and 120% of the initial parameter value. In addition to the sensitivity of key parameters, the sensitivity of the land lease price will be assessed since a strong increase in land for biomass cultivation is likely to increase land lease prices. The sensitivity analysis will be presented using spider diagrams.

4. Data input and assumptions

4.1 Biomass cultivation and harvesting

The costs and GHG emissions in biomass cultivation and harvesting depend on the selected activities, equipment and input materials. This chapter will elaborate on the data input and the assumptions made for the cultivation and harvesting of loblolly pine and hardwood. The discount rate for all costs in biomass cultivation is 6,5% (De La Torre Ugarte et al., 2003).

4.1.1 Feedstock yield

A large range in Loblolly pine yield values in the Southeastern USA region has been found in literature. Where some literature shows a low Loblolly pine yield of around 13 green tonne/ha/year (Jokela, Dougherty, & Martin, 2004; Miller et al., 2003), most give yields between 20.4-29.0 green tonne/ha/year (Antony et al., 2011; Borders & Bailey, 2001; Dickens & Jackson, 2011; Scott & Tiarks, 2008; Zhao & Kane, 2012) and 15.5-16.0 dry tonne/ha/year (Allen, Fox, & Campbell, 2005; Gonzalez et al., 2011). The exact yield values for all sources can be found in Appendix A. An average annual yield of 28 green tonne per hectare per year has been selected here for the whole rotation of the feedstock. While this value seems high, this research assumes an intensive land management which likely results in a high yield. Less data is available for the hardwood yield values in the Southeastern USA region. For this research a hardwood growth yield of 2.2 dry tonne per hectare per year is used based on Gonzalez et al. (2012) and Daystar et al. (2014). This yield value is described for mixed unmanaged hardwood in the southern USA region.

The planting density of trees has an effect on the obtainable yield (Zhao & Kane, 2012). While increasing the planting density from low planting densities will initially increase the total biomass, this yield will finally decrease due to higher competition between trees. Furthermore, higher planting densities will also increase the cultivation costs and emissions per hectare. A wide range exists in literature in the planting density of Loblolly pine. Akers et al. (2013) describe planting densities ranging from 740 up to 4440 trees per hectare. Munsell and Fox (2010) describe that a planting density of 1235 trees per hectare is typically used in mixed product plantations, while a planting density of 1853 trees per hectare is used for increased biomass or pulpwood production. Because of this, a planting density of 1794 trees per hectare at a cost of $76 per 1000 seedlings is assumed (Sunday, Dickens, & Moorhead, 2013). The hardwood considered in this research is unmanaged hardwood and therefore no planting density is necessary for hardwood.

Similar to the yield of loblolly pine a wide range in rotation lengths, which is the time between planting and final harvest, is documented for managed loblolly pine plantations, ranging from 8 to 35 years (Markewitz, 2006; Mills & Stiff, 2008; Munsell & Fox, 2010; Sunday et al., 2013). Since the management system described by Markewitz (2006) is used for the costs and GHG emissions calculations in the cultivation of loblolly pine, the corresponding rotation length of 25 years is used, with thinning in year 14 and 20. During both thinnings 25% of the available biomass is removed from the land. For this research it is assumed that the increased growth of the remaining feedstock after thinning compensates for the removed feedstock, resulting in the same growth yield before and after thinning. The remaining biomass is harvested in year 25. In hardwood cultivation no thinnings are assumed and all biomass is harvested at once at the end of a 50 year rotation period (Daystar et al., 2014).

Table 1 Moisture content and heating values of biomass.

	Loblolly pine	hardwood
Moisture content [a]	45%[a]	47%[b]
HHV dry biomass (MJ/kg)	19.50[c]	19.73[d]
HHV green biomass (MJ/kg)[e]	10.73	10.46
LHV green biomass (MJ/kg)[f]	9.62	9.31

a (Daystar et al., 2014; Gonzalez et al., 2012)

b (Biomass Energy Centre, 2011; Boundy, Diegel, Wright, & Davis, 2011)

c (Reza et al., 2014)

d HHV for mixed hardwood chips used from phyllis2 database

e The higher heating value (HHV) of green biomass is calculated by multiplying the HHV of dry biomass by the dry fraction in the green biomass: $HHV_{green} = HHV_{dry} * (1 - \text{moisture content})$ (Boundy et al., 2011).

f The lower heating value (LHV) of green biomass is lower than the HHV because the evaporated moisture in the biomass is not condensed, and thus the energy required for moisture evaporation is lost. The LHV is calculated using the following equation: $LHV_{green} = HHV_{green} - 2.447 * \text{moisture content}$ (Boundy et al., 2011).

4.1.2 Management practices

In literature, little detailed information is available on the exact selection of management practices for a loblolly pine plantation. While some literature only describe the types and quantities of fertilizers and herbicides that can be used (Mills & Stiff, 2008; Munsell & Fox, 2010; Sunday et al., 2013), other literature only describe potential cultivation equipment. Markewitz (2006) has however described a hypothetical intensive management system, including all equipment and input materials. Even though this study is not very recent, the detailed data is assumed to be fit for the current research. The scheme of management practices described in the article is shown in Table 2. The fertilizer Velpar ULW, which is no longer produced, is replaced by Velpar L at the recommended quantity of 4.7 litre per acre[7].

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[7] Based on ½ gallon per acre described in (DuPont, 1998)

Table 2 Management practices, input materials and costs in Loblolly pine cultivation and harvesting.

Time	Activity	Equipment or product	Equipment time[a]		Material input[b]		Fuel use[c]		Labor costs[d]		Equipment costs	
Site prep	Raking or spot	Skidder	2.2	h/ha			43	L/ha	22.40	$/hour	36.39	$/hour
	herbicide	helicopter	0.024	h/ha			9	L/ha	1302.80	$/hour		
	herbicide	Velpar L			4.68	L/ha						
	plow	Tractor	1.7	h/ha			52	L/ha	22.40	$/hour	36.30	$/hour
Year 1	Machine plant	Skidder	1.5	h/ha			28	L/ha	22.40	$/hour	36.39	$/hour
	NP fertilizer	DAP			224	kg/ha						
	herbicide	helicopter	0.024	h/ha			9	L/ha	1302.80	$/hour		
	Herbicide	Velpar L			4.68	L/ha						
	banded herbicide	glyphosphate			11.2	kg/ha						
Year 2	banded herbicide	glyphosphate			11.2	kg/ha						
Year 6	Fertilizer application	helicopter	0.024	h/ha			9	L/ha	1302.80	$/hour		
	NP fertilizer	DAP			140	kg/ha						
	N fertilizer	urea			432	kg/ha						
Year 14, 20	Fertilizer application	helicopter	0.024	h/ha			9	L/ha	1302.80	$/hour		
	NP fertilizer	DAP			140	kg/ha						
	N fertilizer	urea			432	kg/ha						
Year 14, 20, 25	Commercial thinning and harvest	Feller buncher	9.9	h/ha			216	L/ha	22.40	$/hour	41.81	$/hour
		Skidder	9.9	h/ha			189	L/ha	22.40	$/hour	36.39	$/hour
		Forwarder	9.9	h/ha			211	L/ha	22.40	$/hour	48.25	$/hour

a All equipment times have been taken from Markewitz (2006). The total helicopter time from markewitz has been replaced by the helicopter time per hectare using the fuel consumption per hour (378L/h) and the fuel consumption per hectare (9L/ha).

b The material input quantities are obtained from Markewitz (2006) and are transformed to kg per hectare and Litre per hectare. Velpar ULW is no longer produced and is therefore replaced by Velpar L.

c The fuel consumption per hectare is taken from Markewitz (2006). The values are in line with the fuel use rate and rated power described by Brinker et al. (2002).

d The hourly costs of labor are listed in Appendix B.

e The hourly costs of cultivation and harvesting equipment are listed in Appendix C.

In addition to the management practices and input materials described for Loblolly pine cultivation by Markewitz (2006), site preparation costs are added for prescribed burning (87.89 $/ha) and seedling purchase (138.11 $/ha), as well as annual costs for fire protection and stand management (both 5.02$/ha/year).The additional site preparation costs and annual costs are obtained from Sunday et al. (2013), and are transformed into 2014 dollars per hectare.

The land that is used for biomass cultivation is rented, adding another annual cost for biomass cultivation. Several types of land lease contract designs are described by Yang et al. (2014), in which different constructions are used to pay for the used land. For this research an 'acreage contract' is assumed, meaning that the rental price does not depend on the produced amount of biomass on the land. The land lease price for this research has been set to $153.20[8] per year. These costs include property taxes, and are assumed to remain constant for the whole duration of the project.

A range of silvicultural activities are considered for the cultivation of Loblolly pine, whereas the cultivation of mixed hardwood is assumed to require far less activities (Table 3). The hardwood is unmanaged and does not require any site preparation or application of herbicides and fertilizers. Annual costs for fire protection, stand management and land lease are however considered to prevent loss of the wood plantation.

Table 3 Equipment time, fuel consumption and costs for hardwood harvesting

			Equipment time		Fuel use		hourly wages		Equipment costs	
Year 50	Harvest[a]	Feller buncher	9.9	h/ha	216	L/ha	22.40	$/hour	41.81	$/hour
		Skidder	9.9	h/ha	189	L/ha	22.40	$/hour	36.39	$/hour
		Forwarder	9.9	h/ha	211	L/ha	22.40	$/hour	48.25	$/hour

a The equipment time and fuel consumption are assumed to be the same for hardwood harvesting as for loblolly pine harvesting.

4.1.3 Cultivation and harvesting costs and GHG emissions

Labor

The hourly cost of labor involved in feedstock cultivation and harvesting is listed in Appendix B. Since the amount of necessary labor for feedstock cultivation and harvesting is calculated in hours, the hourly cost is used instead of annual cost. The hourly costs are calculated by adding 30% payroll taxes and fringe benefits to the hourly wages (Campbell, 2007). The wage of the helicopter pilot is not included as these costs are included in the hourly cost of helicopter time.

Fuel, fertilizers and herbicides

The material input quantities and the fuel use for loblolly pine cultivation and harvesting are obtained from Markewitz (2006) and the costs and GHG emissions of the input materials are updated using more recent sources (Table 4). Since the application quantity of Glyphosate is based on the amount of active ingredient, the costs of this herbicide are given per tonne active ingredient.

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[8] This has been calculated using the average rent in Georgia in 2014 of 62$/acre from Escalante (2014).

This research will not consider the use of produced biofuels within the supply chain. All diesel fuel is therefore purchased at the average 2014 diesel price in Georgia. It is assumed that the cultivation and harvesting equipment is solely used on private land, allowing for the use of off-road diesel.

Table 4 Costs and GHG emissions of Fertilizers, herbicides and fuel

Input item	Costs		GHG emissions	
DAP	583.12	\$/tonne[a]	2.04	kg CO_2-eq/kg product[b]
Urea	496.04	\$/tonne[c]	5.66	kg CO_2-eq/kg product[d]
Glyphosate	7054.79	\$/tonne active ingredient[e]	9.22	kg CO_2-eq/kg active ingredient[f]
Velpar L	21.13	\$/litre[g]	2.48	kg CO_2-eq/litre product[h]
Diesel	0.996	\$/litre[i]	2.71	kg CO_2-eq/litre[j]
Off-road diesel	0.873	\$/litre[k]	2.71	kg CO_2-eq/litre[j]

a The costs of DAP are calculated by converting the average 2014 monthly DAP prices from Agweb (2014) (529 $/ton) to $/tonne.

b The GHG emissions of DAP production are 0.73 kg CO_2-eq per kg product, based on 20% elemental phosphorus and 18% elemental nitrogen in DAP (Albaugh et al., 2012). Added to the GHG emissions in DAP production are the GHG emissions in DAP use of 1.3 kg CO_2-eq per kg product (Brentrup & Palliere, 2008).

c The price of urea is taken from Knorr (2015) (450 $/ton), and is converted to $/tonne.

d The GHG emissions of urea production are 0.73 kg CO_2-eq per kg product, based on 46% elemental nitrogen in urea (Albaugh et al., 2012). Added to the GHG emissions in urea production are the GHG emissions in urea use of 4.22 kg CO_2-eq per kg product (Brentrup & Palliere, 2008).

e The costs of Glyphosate are obtained from Ferrell and Sellers (2014). The costs which are given in $/gallon are transformed into costs per tonne active ingredient using a concentration of 5lb active ingredient per gallon (http://extension.psu.edu/agronomy-guide/pm/tables/table-2-4-1a).

f The glyphosate production GHG emissions are 9.1 kg CO_2-eq perkg active ingredient, and the GHG emissions in the use are 1.4 kg CO_2-eq per hectare (Clair, Hillier, & Smith, 2008). These emissions are combined using an assumed application of 11,21 kg active ingredient per hectare (Markewitz, 2006)

g The cost of Velpar L is obtained from Ferrell and Sellers (2014) (80$/gallon), and is converted to $/litre.

h The GHG emissions of Velpar L production are calculated using GHG emissions of herbicide production of 9.1 kg CO_2-eq per kg a.i. (Clair et al., 2008), and an a.i. concentration of 2lb per gallon (DuPont, 1998).

i The average 2014 diesel price in Georgia is obtained from EIA (2015b) (3.77 $/gallon).

j The emission factor of diesel fuel is obtained from EIA (2013). The CH_4 and N_2O emission factors are converted to CO_2-eq using their 100-year GWP (EPA, 2014b).

k In the USA vehicles which are not usually operated on public roadways can receive an exemption of state and federal taxes and fees (EIA, 2015a). In 2014 the average federal and state motor fuel taxes for diesel in Georgia were $0.123 per Litre (0.467$/gallon) (EIA, 2015d).

Cultivation and harvesting equipment

The skidder, tractor, feller buncher and forwarder have a high utilization factor, thus the costs of this equipment is calculated based on the annual fixed costs (e.g. depreciation, interest and insurance costs) and the operational costs (e.g. fuel, lube&oil and R&M) of the equipment. The helicopter used for herbicide and fertilizer application has a lower utilization factor and therefore a company specialized in herbicide and fertilizer application is assumed to be hired at their listed price.

Data from Brinker et al. (2002) is used to find the fixed and operational costs for the equipment used in biomass cultivation and harvesting. The work by Brinker et al. (2002) does not contain information about the Caterpillar D8 mentioned by Markewitz (2006), and therefore the Tigercat S640 has been selected as an alternative machine. This machine is meant for site preparation and is purchased with a plow. Brinker et al. (2002) have given average production hours per year for each machine. This research will however use a higher amount of production hours for all machinery, resulting in lower fixed costs per hour. While increasing the amount of production hours decreases the hourly equipment depreciation, insurance cost and R&M cost, it does not affect the hourly fuel, lube and oil costs. Therefore the annual depreciation of used equipment, which depends on the purchase price, the equipment lifetime and the salvage value, is not influenced by the higher amount of production hours per year. The repair and maintenance (R&M) costs for equipment are calculated by multiplying the annual depreciation by an equipment specific R&M rate (Brinker et al., 2002). The input data for all cultivation and harvesting equipment can be found in Appendix C.

4.2 Transport costs and emissions

The data for the DFC and DVC of biomass transport are obtained from Lu et al. (2015). In their research they describe that loblolly pine trees are left in the forest for 4-8 weeks after felling, which reduces the moisture content in the biomass from 50% to 35%. Since their transport costs mentioned by Lu et al. (2015) are based on dry tonnes, under the assumption of different green biomass moisture content than the biomass modelled in this research, the values cannot directly be used. The DFC and DVC values from Lu et al. (2015) are therefore adjusted to obtain the DFC per actual transported tonne, and the DVC per actual transported tonne-km. This research assumes that the moisture content of the transported biomass does not influence the costs per actual tonne and the costs per actual tonne-km. While the DFC and DVC are described for loblolly pine transport, they are assumed to be the same for hardwood transport. Table 5 shows the DFC and DVC found in Lu et al. (2015), and the adjusted DFC and DVC for the current investigation.

Table 5 Distance fixed costs and distance variable costs for biomass transport

Dry tonne[a]	DFC	4.32	\$/dry tonne
	DVC	0.134	\$/dry tonne-km
Green tonne[b] (35% moisture)	DFC	2.81	\$/actual tonne
	DVC	0.087	\$/actual tonne-km

a The values for DFC and DVC are obtained from Lu et al. (2015).

b The DFC and DVC which are based on dry tonnes are converted into costs per green tonne, using the moisture content of 35% from Lu et al. (2015). The calculated values are in line with values of Elia et al. (2013); DFC of 3.32$/green tonne and a DVC of 0.077$/green tonne-mile.

The GHG emissions for the transport of biomass are shown in Table 6. Similar to the DFC and the DVC, the GHG emissions per dry tonne-km, obtained from Lu et al. (2015), are converted to GHG emissions per actual tonne-km.

Table 6 GHG emissions from biomass transport

Dry tonne[a]	174.3	g CO_2-eq/dry tonne-km
GHG emissions[b]	113.3	g CO_2-eq/actual tonne-km

a (Lu et al., 2015)

b The GHG emissions per actual transported tonne are calculated using the biomass moisture content of 35% in Lu et al. (2015).

To calculate the transport costs, the annual demand for green biomass must be known. The parameters and assumption necessary to calculate this annual biomass demand can be found in Table 7.

Table 7 Biomass transport input data.

Operating days per year[a]	350	day's/year
Annual dry biomass demand[b]	700,000	dry tonne/year
Moisture content dry biomass	0%	
Annual green Loblolly pine demand[c]	1,272,727	green tonne/year
Annual green hardwood demand[c]	1,320,755	green tonne/year
Fraction of land usable for biomass production (f)[d]	90%	
Tortuosity factor (τ)[e]	1.2	
Ratio round trip : loaded trip (r)[f]	1.7	* av. Transport distance

a The operating days per year are based on an uptime of 96% (Aden et al., 2002; Gonzalez et al., 2012; Humbird et al., 2011b; Kazi et al., 2010). The amount of days is rounded to an integer.

b The annual biomass demand is calculated using the operating days per year, and a plant capacity of 2000 dry tonne per day.

c The annual biomass demand in green tonne is calculated by dividing the annual dry biomass demand by the dry biomass fraction in the green biomass.

d Even though Wright and Brown (2007b) use a fraction of land usable for biomass production of 60%, this research will assume a relatively high fraction of 90%. While the selected value is high compared to other studies, this thesis also applies an tortuosity factor, which has a similar effect as a lower fraction.

e Wright and Brown (2007b) describe that a tortuosity factor between 1.2 and 3.0 can be used to calculate the actual average transport distance. This research applies a tortuosity factor (τ) of 1.2 as the wood industry in the Southeastern USA region is well developed.

f Han (2011) found that the costs for truck transport without back-hauling are between 66% and 90% higher than the costs for transport with backhauling. Based on this data this research will assume the round trip costs and emissions to be 70% higher than the single transport trip costs and emissions. Since the distance variable costs and emissions depend on the average transport distance these values will be calculated using the fictive round trip distance which is 70% larger than the actual single trip distance.

4.3 Biomass processing

The costs in biomass processing consist of several different cost factors. In general the costs can be divided in the investment costs and the operational costs and GHG emissions.

4.3.1 Investment costs

The investment costs include the purchase of necessary equipment, installation of the equipment and a range of additional costs that are based on the total installed equipment costs. In order to annualize the investment costs the economic lifetime of the capital is used.

Mass balance

The use of mass balances is necessary for some conversion technologies when the cost data of specific processes within the conversion technology are based on the weight of the input and output in those processes. In some of the used literature the costs are based on the capacity of the whole facility, eliminating the need of mass balances for all processes in the conversion technology.

Installation factor

For several of the conversion technologies an installation factor (IF) is given for each component. The IF is a factor that accounts for a set of direct costs involved in the installation of equipment, and is given as a percentage of the bare costs of equipment (Meerman, 2012). If the installation factor is not given for a conversion technology it is assumed that the base scale equipment costs already include the installation costs.

Additional costs

In addition to the installed equipment costs a range of costs are added for direct and indirect costs. Most data in the economic analysis of conversion technologies concern the costs of specific equipment used in the conversion processes. The additional direct and indirect costs are however dealt with less extensively. In Jones et al. (2013) the direct costs are described as the sum of the installed equipment costs, building costs, piping and site development. The costs for the building, piping and site development are calculated as a percentage of the installed equipment costs, with values of 4%, 4.5% and 9% respectively (Humbird et al., 2011b; Jones et al., 2013). While the direct costs described above are assumed accurate for fermentation, gasification with fischer-tropsch and pyrolysis, this is not usable for pelleting and the TOP process due to the lower equipment costs for these conversion technologies. Instead, the costs for the TOP process and pelleting buildings are calculated using the scaled construction costs from Mobini et al. (2013) and the direct contingency costs are calculated as 10% of the total installed equipment costs (Pirraglia, Gonzalez, Saloni, & Denig, 2013). The indirect investment costs for all conversion technologies are calculated as 60% of the installed equipment costs (Humbird et al., 2011b; Jones et al., 2013).

Discount rate

A significant degree of uncertainty exists in the discount rate used for renewable technologies (Oxera, 2011). The report produced by Oxera shows that a discount rate between 9% and 13% can be assumed for biomass projects (real, pre-tax). This research will therefore use a discount rate for the conversion plants of 11%. The discount rate for the conversion plant investment is significantly higher than the discount rate used for the cultivation process due to the higher risk of the investment.

Lifetime

The total capital investment at the start of the project is annualized using the EAC method in Equation 3.12. In this equation an economical lifetime of 15 years for all capital is applied (Hamelinck et al., 2004; Humbird et al., 2011a).

4.3.2 Operational costs and GHG emissions

The operational costs in biomass processing are the annual costs for labor, maintenance, insurance, taxes, input materials and energy. GHG emissions in biomass processing are calculated using the purchased input materials and energy, and the sold by-products.

Labor

The assumed necessary labor for each conversion technology is shown in Table 8. For pyrolysis, gasification and fermentation data is available on the recommended amount of labor. For the other conversion technologies one plant manager, one plant engineer, one maintenance supervisor and five shift supervisors are assumed to be required, which is in line with the labor for the other conversion technologies.

Table 8 Labor requirement conversion factories

Position Title	Annual salary costs ($2014)[h]	Pellet[a,b]	TOP[a,c]	Gasification +FT[d]	Fermen-Tation[e]	Pyrolysis[f]
Plant Manager	$ 169,865	1	1	1	1	1
Plant Engineer	$ 100,369	1	1	1	1	1
Maintenance Super	$ 65,883	1	1	1	1	1
Lab Manager	$ 64,725	0	0	1	1	1
Shift Supervisor	$ 64,834	5	5	5	5	5
Lab Technician	$ 46,202	1	1	2	2	3
Maintenance Tech	$ 55,572	4	5	8	8	16
Shift Operators	$ 46,310	20	20	40	40	40
Yard Employees	$ 32,310	8	8	12	8	12
Clerks & Secretaries	$ 40,208	5	5	3	5	3
Forklift operator	$ 46,310	5	5	0	0	0
General manager	$ 108.701	1	1	1	1	1
Financial manager[g]	$ 108.971	1	1	1	1	1
Marketer[g]	$ 71.223	2	2	2	2	2
executive/administrative assistant[g]	$ 61.445	1	1	1	1	1
Accountant[g]	$ 82.993	2	2	2	2	2
Total FTE		58	59	81	79	90

a For pelletizing and torrefaction no lab manager is taken into the calculations since it is assumed that these conversion technologies require less lab work. However one lab technician is incorporated for both technologies in order to monitor and maintain quality of production

b The amount of labor necessary for a pelletization factory is based on the labor data for TOPs. Since the pelletization plant uses less equipment than the torrefaction and pelletization plant less maintenance technicians are selected for this plant. The amount of shift operators, yard employees, clerks and secretaries and forklift operators are the same as for the TOP factory.

c The necessary labor for a combined torrefaction and pelletization factory is based on research of Pirraglia et al. (2013). In their work they describe the labor for a conversion plant producing 100.000 tonne pellets per year. Since the scale of the TOP production plant in this research is approximately 5 times larger than the scale applied in Pirraglia et al. (2013) it is assumed that 5 times as much employees are required for production, forklift operating, maintenance and raw material handling. In addition to the labor described by Pirraglia et al. (2013), 8 yard employees are added.

d The necessary amount of labor for a combined gasification and FT facility are taken from Phillips et al. (2007). While Phillips et al. (2007) mention the use of 20 shift operators this research will assume 40 shift operators, similar to the pyrolysis processing factory. Having 20 shift operators would result in 5 operators per shift which is assumed to be too little for a large scale processing factory.

e The necessary labor for a fermentation plant is taken from Wooley et al. (1999).

f The recommended amount of labor for pyrolysis is obtained from Jones et al. (2013).

g The amount of labor for financial manager, marketer, executive/administrative assistant and accountant for all conversion technologies are obtained from Pirraglia et al. (2013). The amount of labor for these functions is assumed to be independent on the scale of the processing factory.

h The hourly wages for all function are obtained from www.payscale.com, bls.gov. The annual costs of each function is calculated assuming 2080 working hours per year, and with the addition of 30% payroll taxes and fringe benefits (Campbell, 2007).

Maintenance, insurance and taxes

The annual maintenance costs for pelletizing capital in this research is the sum of 18% of the installed hammer mill costs, 10% of the installed pellet mill and 2.5% of the remaining equipment costs (Sultana, Kumar, & Harfield, 2010). The maintenance costs for the TOP factory are based on the annual torrefied pellet production and are 9.31 \$/tonne output (Pirraglia et al., 2013). The maintenance costs of the fermentation factory and the combined gasification and FT factory are both 2% of the installed equipment costs (Swanson et al., 2010a), while the maintenance costs of the pyrolysis plant are 3% of the total investment costs (Jones et al., 2013).

The insurance and taxes for all conversion factories is assumed to be 0.7% of the total capital investment (Humbird et al., 2011b; Jones et al., 2013).

Energy costs and emissions

Different types of energy are utilized for the conversion of biomass to bioenergy. The costs and GHG emissions of the used types of energy are shown in Table 9. The electricity purchased from the grid by the conversion plant is retail electricity, while excess electricity sold to the grid is wholesale electricity.

Table 9 Energy costs and GHG emissions

	Costs		GHG emissions	
Electricity retail[a,c]	0.0657	\$/kWh	0.617	kg CO_2-eq/kWh
Electricity wholesale[b,c]	0.0425	\$/kWh	0.617	kg CO_2-eq/kWh
Natural gas[d,e]	5.52	\$/1000 ft^3	54.4	kg CO_2-eq/1000 ft^3

a The electricity price used in this research is the average retail price of electricity to the end-use sector 'Industry' in Georgia in February 2014 (EIA, 2015c).

b The electricity wholesale price is the average 2014 electricity price at trading hubs in the Southeastern USA region, obtained from EIA (EIA, 2015i).

c The GHG emissions for electricity are for the Southeastern USA region (EPA, 2014a).

d The natural gas price used in this research is the Industrial price for natural gas in Georgia, for November 2014 (EIA, 2015f)

e The GHG emissions for Natural gas are obtained from EIA (2013).

4.3.3 Pretreatment

For biomass to be converted into bioenergy the biomass must first be pretreated. Most conversion technologies require the biomass to be dried and reduced in size before it can be used in a conversion plant. Data on the costs and GHG emissions of pretreatment for all conversion technologies is available, but due to the divers values found in literature, this research will use standardized assumptions for all conversion technologies.

Drying

To determine the necessary scale for the drying equipment, both the biomass capacity and the moisture capacity are of importance. While the biomass capacity shows how much green biomass can be processed by the equipment per hour, the moisture capacity reflects the amount of water that can be evaporated by the dryer per hour. Since it is not known which size dryer gas blower and dryer gas filter are necessary, the costs of these equipment types will be added as a percentage of the dryer equipment costs. Based on the selected equipment items for the refinery cases in Cherry et al. (2013) costs equal to 40% of the rotary drum dryer costs will be assumed for the dryer gas blower and dryer gas filter equipment. Since the ratio between the biomass capacity and the moisture capacity is the same for all dryers in Cherry et al. (2013) the largest scale is used as the base scale, in combination with a scaling factor of 0.75 (Phillips et al., 2007). The dryer equipment data can be found in Table 10.

Table 10 Selected capital costs for drying equipment

Component	base scale (tonne/hour)	base scale (tonne/hour evap)	base scale cost equipment	Base year	scaling factor
Dryer+dryer gas blower/filter[a]	133.4	26.7	$ 3,812,200	2011	0.75[b]

a The base scale dryer costs in Cherry et al. (2013) are $2,723,000 for a dryer with a biomass capacity of 133.4 tonne per hour and a evaporation capacity of 26.7 tonne per hour. The dryer gas blower and the dryer gas filter equipment are added to the base scale cost as 40% of the dryer cost from Cherry et al. (2013).

b (Phillips et al., 2007)

The pretreatment of biomass within conversion technologies requires both electricity and heat. While the grinding and cooling of biomass only require electricity, the drying process requires both heat and electricity (Mobini et al., 2013). As shown in Figures 4, 5, 6 and 7, several of the conversion technologies produce by-products that can be used to provide energy for processes in the conversion plant, which reduces the demand for energy from outside the facility. The amount of energy necessary for pretreatment depends on the biomass characteristics requirements of the applied conversion technology after pretreatment. If the conversion technology does not produce enough by-products to provide heat for drying, the remaining heat can be generated by burning fuel material (Mobini et al., 2013), for this study assumed to be biomass. It is however important to note that this biomass is counted within the conversion plant capacity of 2000 dry tonne/day, and will thus decrease the biomass used for bioenergy production. In some biomass to bioenergy conversion factories the parts of the biomass which have less desirable characteristics for bioenergy production (e.g. bark) are used to produce heat. Since the calorific values found in the Phyllis database are close to the calorific values of whole tree loblolly pine and hardwood, the same values will be used.

The drying of biomass takes place in a rotary drum dryer, the most commonly used technology in wood biomass drying (Mobini et al., 2013). The heat required for evaporating one tonne water in the biomass drying process using a rotary drum dryer is 1000 kWh (Ciolkosz & Wallace, 2011; Ehrig, Behrendt, Wörgetter, & Strasser, 2014; Uasuf, 2010). Taking 10% heat loss into account (Ehrig et al., 2014; Uasuf, 2010), the heat demand for drying is 4000 MJ/tonne water evaporated for a dryer using biomass as fuel,. If biomass is used as fuel material for drying, the necessary amount of biomass is calculated using the weight of water that should be evaporated, the heat demand for drying and the heating value of the used green biomass.

In addition to the heat used for drying, the drying process consumes electricity for the belt drive, fans and other electrical components. The electricity consumption for the drying process is 9.22 kWh/t dry biomass input[9] (Mobini et al., 2013). During this process the weight of the biomass reduces due to the extraction of moist. It is however assumed that no biomass is lost during this process. The biomass which remains after drying is not totally dry (0% moisture), and thus has a larger weight than the conversion plant capacity which is given in dry weight.

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[9] The calculated value 9.22 kWh/t green biomass input is based on a drying electricity consumption of 1.1 GWh for the production of 93.3 ktonne pellets, and 26.02 tonne water evaporated (Mobini et al., 2013).

Size reduction

Similar to the drying equipment costs, the grinding equipment costs are standardized for all conversion technologies. The base scale size and cost can be found in Table 11. Here an energy consumption for size reduction of 33.9 kWh per tonne biomass[10] is used based on work by Mobini et al. (2013). During the size reduction of biomass it is assumed that no loss of mass takes place (Uslu et al., 2008).

Table 11 Selected capital costs for biomass size reduction.

Component	Base scale	unit	base scale cost equipment	Base year	scaling factor
Chopper+Grinder[a]	2000	dry tonne/day feedrate	$ 3,359,012	2007	0.7

a The Chopper and grinder costs concern the combined costs of the chopper, chopper conveyor, chopper screen with recycle conveyor, grinder, grinder conveyor and grinder screen with recycle conveyor. All costs and the scaling factor are obtained from Swanson et al. (2010).

4.3.4 Pelleting

In pelletizing, green biomass is first pretreated to obtain grinded biomass with a moisture content of 6% (Pirraglia, Gonzalez, & Saloni, 2010). The modelled processes for pelleting do not produce any by-products, and therefore all heat is provided by burning biomass whitless desirable characteristics.

The amount of energy used by the processes in pelletizing is obtained from Mobini et al. (2013). By multiplying the power of the equipment (kW) by the simultaneity factor of the equipment, and dividing this value by the processed weight or capacity per hour, the energy consumption per tonne is obtained. Mobini et al. (2013) use a capacity of 5 and 10 t/h with an equipment power of 300 and 25 kW respectively for the pellet mill and the cooler. The given capacities are equal to the weight of the pellets which are produced. For all equipment a simultaneity factor of 85-100% is given hence here the average simultaneity factor of 92.5% is used.

Table 12 Selected capital costs of the components for a pelleting factory.

Component	base scale	unit	base scale cost equipment[a]	# required	Installation factor	Base year	scaling factor[b]
Pellet mill	20	t pellets/h	$ 2,878,614	4	1.51	2013	0.85
Cooler	20	t pellets/h	$ 1,097,768	2	1.75	2013	0.58
Screener	20	t pellets/h	$ 90,477	1	1.58	2013	0.6
Conveyers, tanks, etc.	20	t pellets/h	$ 6,591,947	1	1.40	2013	0.75
Buildings	20	t pellets/h	$ 4,300,000	–	1.00	2013	0.7

a The base scale costs are are obtained from Mobini et al. (2013) for a pelleting plant producing 20 tonne pellets per hour. The new scale pelleting plant must therefore be scaled based on its output.

b The scaling factors for pelleting equipment are taken from Sultana et al. (2010).

Mobini et al. (2013) determined the energy consumption of the pelletizing processes based on the weight of the produced pellets. Using a simultaneity factor of 92.5% the electricity consumption for pelletizing is 55.5 kWh/tonne pellets produced, and for cooling 2.3 kWh/tonne pellets produced.

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10 The energy consumption for size reduction has been calculated using the capacity and power from Mobini et al. (2013), and an assumed simultaneity factor of 92.5%.

While no biomass is lost during drying and size reduction, the pelletization process has a biomass loss of 1% (Damen & Faaij, 2006; Ehrig et al., 2014), however, during cooling no additional biomass is lost. Cooling takes place at the end of the conversion process using a counterflow cooler (Ehrig et al., 2014). The moisture content of produced pellets is 6% (Pirraglia et al., 2010).

4.3.5 TOP process

For torrefaction the energy yield and the mass yield depend on the torrefaction temperature and the process time (Ciolkosz & Wallace, 2011). The yield of solid material is highest when torrefaction takes place at a low temperature, and when a short processing time is applied (Carrasco, Oporto, Wang, & Zondlo, 2013; Ciolkosz & Wallace, 2011). A typical solid yield of pine torrefaction at 230°C, and 60 minutes processing time, is 92.4% with the remaining output being gas (0.6%) and liquid (7%) (Ciolkosz & Wallace, 2011). Increasing temperature and duration of the torrefaction process, also increases the difference between the energy yield and the mass yield (Almeida, Brito, & Perré, 2010; Kim, Lee, Lee, & Lee, 2012), meaning that the energy density of the torrefied material increases. Since the heat for biomass drying can be provided by the combustion of torrefaction gases it may not be desirable to use a torrefaction process that produces a low gaseous yield. Furthermore, an additional advantage of using a higher torrefaction temperature is the increased energy density of the produced torrefied solid material.

Batidzirai et al. (2013) produced a mass and energy balance for biomass torrefaction at a temperature of 275°C and a reaction time of less than 60 minutes. They describe that a facility which uses biomass with a moisture content of 40% needs to burn 4% of the biomass, together with the produced torgas and flue gas, to provide all necessary heat for drying and torrefaction. While they produced the mass balance for an torrefaction facility using eucalyptus as feedstock the data is assumed to be usable for this research since the heating value applied for eucalyptus with 40% moisture (10.9 MJ/kg) is similar to the calculated heating value of loblolly pine and mixed hardwood with 40% moisture (10.72 MJ/kg and 10.86 MJ/kg respectively).

To ease calculations two pretreatments stages are modeled before biomass torrefaction takes place. During the first pretreatment biomass is dried to 40% moisture content using biomass as fuel. In the second pretreatment the moisture content of the biomass is further reduced to 20% using 4% of the biomass after the first pretreatment and the torgas and flue gas from the torrefaction process.

Based on Pirraglia, Gonzalez, Saloni, & Denig, (2013) it is assumed that 26.8% dry mass loss takes place during torrefaction, which is in line with Batidzirai et al. (2013). The energy yield of the TOP process is 81.29% (Ben & Ragauskas, 2012; Carrasco et al., 2013).

Similarly to pelletizing, the torrefaction process requires both heat and electricity. All necessary heat for torrefaction is provided by burning biomass, torgas and flue gas (Batidzini et al., 2013). While the torrefaction process also requires electricity it has not been added in the model since it is assumed that the lower electricity consumption for size reduction during pretreatment, as compared to conventional wood pellet production, compensates for the electricity consumption in torrefaction (Koppejan, Sokhansanj, Melin, & Madrali, 2012). The pelletization process after torrefaction however consumes more electricity, with an electricity consumption of 150 kWh/tonne TOPs produced (Koppejan et al., 2012). The cooling process is assumed to require the same electricity per cooled tonne as in the pelletizing conversion technology.

Table 13 Selected capital costs for the TOP process factory

Component	base scale	unit	base scale cost per unit[a]	# req.	Installation factor[a]	Base year	scaling factor[b]
Torrefaction unit	100,000	t TOPs/year	$ 7,078,686	4	1.00	2011	0.7
Live bottom bin	100,000	t TOPs/year	$ 18,226	20	1.83	2011	0.7
Continuous dual-shaft biomass mixer	100,000	t TOPs/year	$ 480,000	2	1.45	2011	0.7
Hammer mill	100,000	t TOPs/year	$ 83,537	2	1.45	2011	0.7
Pellet mills(s) (including conditioning)	100,000	t TOPs/year	$ 265,798	2	1.31	2011	0.85
Boiler/water heater	100,000	t TOPs/year	$ 167,073	1	1.01	2011	0.7
Counterflow cooler 1&2[c]	100,000	t TOPs/year	$ 227,827	8	1.08	2011	0.7
Screener 1&2[c]	100,000	t TOPs/year	$ 15,188	8	1.80	2011	0.6
Buildings[d]	20	t pellets/h	$ 4,300,000	-	1.00	2013	0.7

a The base scale costs and IF are obtained from Pirraglia et al. (2013) for a TOPs plant producing 100,000 tonne pellets per year.

b While several of the components require multiple units Pirraglia et al. (2013) apply a scaling factor of 0.7 for all components. The scaling factor for the pellet mills and the screeners are obtained from Mobini et al. (2013).

c The counterflow cooler and the screener are both mentioned twice in Pirraglia et al. (2013). Since the counterflow coolers have the same base scale, costs and installation factor they are added together, and thus the number required is doubled. The same is performed for both screeners.

d (Mobini et al., 2013)

4.3.6 Gasification with FT

Before gasification can take place biomass is pretreated to reduce the moisture in biomass to 15% using a combination of biomass and the by-product heat. In combined gasification and FT several of the involved processes produce excess heat, while several of the processes demand heat (Meerman, 2012). The heat streams can be combined in a heat recovery steam generation (HRSG) system and if the system subsequently still contains excess heat, a steam turbine can be used for electricity generation (Meerman, 2012). In their research Kreutz et al. (2008) assume that 5.2% of the initial energy (HHV) of the used biomass can be converted into electricity. This current work however assumes that this energy will be used for biomass drying during pretreatment instead of electricity production. It is then important to note that both the biomass demand for drying and the by-product production depend on each other.

The energy content of the FT diesel after the FT process contains 27.6% of the initial energy content in the used biomass, while the FT gasoline contains 17.7% of the initial energy[11] (Kreutz et al., 2008).

Since the combined gasification and FT process is capable of producing more electricity than the factory demands, no electricity needs to be purchased. Annual costs are however added for cooling water, waste disposal and hydroprocessing, based on (Swanson et al., 2010a). Since the values mentioned by Swanson et al. (2010) are based on a conversion facility using 2000 dry tonne biomass per day the values will be adjusted.

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[11] Kreutz et al. (2008) describe that a BTL-RC-V configuration with a biomass input of 660 MW HHV has an output of 182 MW HHV FT diesel, and 117 MW HHV FT gasoline.

Table 14 Selected capital costs for the combined gasification and FT of biomass.

Component	base scale	unit	base scale cost per unit[a]	# req.	Base year	scaling factor
ASU, and O2 and N2 compression	3,041	dry tonne/day	$ 94,000,000	1	2007	0.8[b]
Biomass handling, gasification, and gas cleanup	3,041	dry tonne/day	$ 266,000,000	2	2007	0.67[c]
All water gas shift, acid gas removal, Claus/SCOT	3,041	dry tonne/day	$ 58,000,000	1	2007	0.68[d]
CO_2 compression	3,041	dry tonne/day	$ 1,000,000	1	2007	0.67[f]
Fischer-Tropsch synthesis & refining, recycle compressor, ATRs	3,041	dry tonne/day	$ 126,000,000	1	2007	0.71[e]
Naptha upgrading to gasoline (isomerization, catalytic reforming)	3,041	dry tonne/day	$ 26,000,000	1	2007	0.65[f]
Heat recovery and steam cycle	3,041	dry tonne/day	$ 64,000,000	1	2007	0.85[f]

a The base scale data has been obtained from Kreutz et al. (2008), who describe a BTL-RC-V configuration. This is a process configuration which uses biomass as input (BTL),which recycles unconverted syngas to maximize FTL production (RC), and vents the coproduct CO_2 (V).

b The scaling factor for the ASU has been taken from Meerman (2012).

c Meerman (2012) gives a scaling factor of 0.66 for a Shell EF gasifier, while Kreutz et al. (2008) give a scaling factor of 0.67. This research will use a scaling factor of 0.67.

d Meerman (2012) gives scaling factors ranging from 0.65 to 0.7 for the different equipment in WGS and Acid gas removal. An overall scaling factor of 0.68 will be used for this research.

e Meerman (2012) gives a scaling factor of 0.72 for the FT reactor, and 0.7 for the FT upgrading equipment. A combined scaling factor of 0.71 will be assumed.

f (Kreutz et al., 2008)

4.3.7 Fermentation

Gonzalez et al. (2011) have looked at the economics of ethanol production from both loblolly pine and mixed southern hardwoods, using green liquor. Green liquor is an intermediate product in kraft pulping, and its process can be used to pretreat lignocellulosic feedstock for the production of ethanol (Gonzalez et al., 2011). According to Gonzalez et al. (2011) pretreatment with green liquor is attractive since the necessary technology is already being used, resulting in experience in operations and up-scaling. Their work will be used for the calculations in the conversion technology for hydrolysis and fermentation.

In the hydrolysis and fermentation process biomass does not need to be dried during the pretreatment. In the hydrolysis and fermentation cost data, obtained from Gonzalez et al. (2011), equipment costs for ‘chip receiving’ are given which presumably includes costs for transport and grinding of biomass. For this research the chip receiving costs will however be replaced by the standardized grinding equipment costs since it is unclear which costs are included in the chip receiving costs. While using this method might neglect some cost factors that are incorporated into the chip receiving costs, it will allow for a better comparison between the conversion technologies.

Based on research by Daystar et al. (2013) the applied yield value for the conversion of mixed hardwood into ethanol is 356.3 Litre/dry tonne and for the conversion of loblolly pine into ethanol is

369.6 Litre/dry tonne. These values are in line with Frederick et al. (2008) and Humbird et al. (2011). The heating value of the produced ethanol is 21 MJ/litre (Wright & Brown, 2007b).

Through the combustion of lignin and biogas, the hydrolysis and fermentation conversion technology is capable of producing more electricity than the processes consume and therefore 12,797 kW (Humbird et al., 2011b) of electricity can be sold to the grid (Gonzalez et al., 2011; Humbird et al., 2011b) at the wholesale electricity price.

In hydrolysis and fermentation, costs are added by the purchase of glucose for enzyme production, chemicals and yeast. While Gonzalez et al. (2011) assumed that all enzyme is purchased this current study will use equipment for the production of enzymes as stated in Humbird et al. (2011b) to reduce the annual costs for enzyme purchase. The costs of the glucose necessary for enzyme production are 0.06 $/litre ethanol (Humbird et al., 2011b) and the costs for chemicals and yeast are 0.01 $/litre ethanol and 0.02 $/litre ethanol respectively (Gonzalez et al., 2011).

The GHG emissions in fermentation are obtained from Daystar et al. (2013), and are 0.54 g CO_2-eq/litre ethanol from Loblolly pine and 0.61 g CO_2-eq/litre ethanol from hardwood.

Table 15 Selected capital costs for the fermentation of biomass.

Component	base scale	unit	base scale cost per unit	Base year	scaling factor
Green liquor pretreatment	453,597	dry t/year	$ 30,373,350	2010	0.6
Mechanical post treatment	453,597	dry t/year	$ 5,528,526	2010	0.6
Oxygen post treatment	453,597	dry t/year	$ 18,597,603	2010	0.6
Enzyme post treatment	453,597	dry t/year	$ 48,619,292	2010	0.5
Enzyme production[b]	700,920	dry t/year	$ 25,416,667	2007	1.0[c]
Lignin filter	453,597	dry t/year	$ 12,525,287	2010	0.6
Fermentation	453,597	dry t/year	$ 22,074,022	2010	0.8
Beer column	453,597	dry t/year	$ 5,011,199	2010	0.8
Rectification column	453,597	dry t/year	$ 4,653,067	2010	0.8
Dehydration	453,597	dry t/year	$ 5,139,166	2010	0.7
Evaporation	453,597	dry t/year	$ 28,409,692	2010	0.6
Recovery boiler	453,597	dry t/year	$ 59,475,156	2010	0.6
Turbine generator	453,597	dry t/year	$ 28,100,034	2010	0.5

a The base scale costs and scaling factors for all components other than the enzyme production are obtained from Gonzalez et al. (2011). The base scale unit of all components is dry tonne biomass input per year.

b Humbird et al. (2011) give an equipment costs of 20,9 million dollar for the biochemical conversion of corn stover to ethanol at a conversion plant capacity of 2000 dry tonne per day and an uptime of 96%. Treasure et al. (2014) however mention that loblolly pine and natural hardwood require more enzymes than corn stover. Based on Treasure et al. (2014) this research will assume that the equipment costs for enzyme production are 39% higher for loblolly pine and natural hardwood than for corn stover.

c The scaling factor of the enzyme production equipment is assumed to be 1.0 since the highest cost components all have a scaling factor of 1.0 (Humbird et al., 2011b).

4.3.8 Pyrolysis

Before pyrolysis takes place biomass is pretreated to reduce the moisture content in the biomass to 10%, and to reduce the biomass in size (Bridgwater, Toft, & Brammer, 2002; Jones et al., 2013). Jones et al. (2013) show that the pyrolysis conversion technology produces char with a weight equal to 12% of the converted dry biomass. The char can be used in a combustor to produce heat for biomass drying and for the pyrolysis process (Wright et al., 2010). With a heating value of approximately 28.5 MJ/kg char (Jones et al., 2013), 121% of the heat demand for loblolly pine drying or 110% of the heat demand for hardwood drying can be provided by char combustion. Since the heat required for the pyrolysis process is provided by char combustion too, it is assumed that the excess heat after hardwood drying exactly covers the heat demand for hardwood pyrolysis. Due to the lower heat requirement for Loblolly pine drying, the pyrolysis of loblolly pine results in unused heat which can be used to produce electricity. A conversion efficiency of 40% is assumed for electricity production within the pyrolysis factory. The produced electricity is used for own consumption, resulting in a lower purchase of electricity from the grid.

For the production of bioenergy through pyrolysis natural gas and electricity are required. To generate hydrogen, which is used for hydrotreating, 5.28 scf natural gas is purchased per produced litre blendstock (Jones et al., 2013). The electricity consumption of the processes involved, which is purchased from the grid, is 0.34 kWh per litre blendstock (Jones et al., 2013). Additional costs are assumed for the pyrolysis process for Catalysts & Chemicals ($21.5 Million per year) and for waste disposal ($526,000 per year) (Jones et al., 2013).

The pyrolysis conversion technology produces both gasoline and diesel. Based on Jones et al. (2013) the production yield used for this research is 166 litre gasoline and 182 litre diesel per dry tonne biomass. The heating value of the produced fuel is 11.7 MJ per dry tonne biomass (Jones et al., 2013).

4.4 Reference fossil fuels

The costs of gasoline and diesel production are calculated by multiplying the average 2014 retail prices of the fossil fuels by 65% for the crude oil costs, and by 13% for the refining costs (AFPM, 2015). It is however important to note that crude oil prices are volatile (EIA, 2015g), and that it is therefore difficult to predict future crude oil prices. For instance the retail price of diesel in the lower Atlantic region has been as low as 0.30$/litre in 2002, while prices have reached 1.24 $/litre in 2008 (EIA, 2015e). For this thesis the average 2014 fossil fuel prices are used. The costs of the reference fossil fuels are listed in Table 16.

Table 16 Costs and GHG emissions in the reference fossil fuels.

Diesel production costs[a]	0.777	$/litre	21.70	$/GJ
Gasoline production costs[b]	0.722	$/litre	22.28	$/GJ
Coal[c]	3.03	$/MMBtu	2.87	$/GJ

a The average 2014 diesel price in Georgia (3.77 $/gallon) is obtained from EIA (2015e). The costs per litre are converted into costs per GJ using an energy density of 35.8 MJ/litre.

b The used gasoline price (3.503 $/gallon) is the average 2014 price for midgrade gasoline in Georgia (EIA, 2015h). The costs per litre are converted into costs per GJ using an energy density of 32.4 MJ/l.

c The costs for coal are taken from EIA (2015b).

The emission factors for the reference fossil fuels are obtained from EIA (2013), and are multiplied by ERE values taken from Blok (2007). The used ERE values, which are listed in Table 17, are the average values of the ranges described in Blok (2007), excluding the indirect energy for transport after refining.

Table 17 Emission factors and energy requirement for energy values for reference fossil fuels.

	Emission factor[a]		ERE[b]
Bituminous coal	88.4	g CO_2-eq/MJ HHV	1.02
motor gasoline	67.5	g CO_2-eq/MJ HHV	1.08
diesel fuel	69.3	g CO_2-eq/MJ HHV	1.08

a (EIA, 2013)

b Blok (2007) gives an ERE for coal of 1.04-1.10 which includes an indirect energy requirement of 0-7% for transport, and an ERE of 1.08-1.15 for oil products which includes an indirect energy requirement of 3% for transport.

4.5 Sensitivity Analysis

A large variety exists in the expected yield values found in literature for Loblolly pine and mixed hardwood. The selected yield value has a significant effect on both the GHG emissions and the costs of the bioenergy supply chain. Most values calculated in the biomass cultivation phase are costs and GHG emissions per hectare, and will therefore remain the same at different yield values. Since the biomass volume obtained per hectare changes at different yield values, the costs and GHG emissions per tonne will change. Jacobson and Ciolkosz (2013) assume an annual increase of 1% in energy crop yields, which accounts for the learning in planting and for the improvements in breeding and selection of better varieties. Performing a sensitivity analysis on the biomass yield will therefore show how future costs and GHG emissions of the configurations will change due to higher yield values. The yield used for loblolly pine and hardwood will both be increased and decreased by 20%.

The discount rate used for biomass cultivation in this study is 6.5%. Since the cultivation costs of hardwood have a large effect on the supply chain costs, the value of this discount rate will be tested. The discount rate will ranged from 5% to 8%, resulting in a decrease and increase in the discount rate of 23%.

The EAC shows what the annual costs of the total capital investment are for a supply chain. A range of parameters however influence the value of the EAC (e.g. the total capital investment, lifetime of capital and the discount rate). In order to take an uncertainty of all parameters into account the EAC will be increased and decreased by 20%. Using a 20% lower EAC value is the equivalent effect of a discount rate for conversion plants of 7.2% or a capital lifetime of 43 years, while using a 20% higher EAC value is the equivalent effect of a conversion plant discount rate of 14.5% or a capital lifetime of 10.3 years. It is important to note that changing the EAC does not affect the total capital investment and therefore has no influence on the operational costs.

One of the uncertainties is the moisture content of the transported and pretreated biomass. This investigation has assumed that the moisture content of the transported and pretreated biomass has the same moisture content as when it is harvested. A part of the used literature however assumes that the biomass remains on the land to dry after harvesting, before transport takes place. For both feedstock types the effect of this natural drying will be analyzed, assuming a moisture content of 30%. For loblolly pine this is a 33.3% reduction in moisture content, while fore hardwood the moisture content reduction is 36.2%.

The land lease costs appear to have a large influence on the cultivation costs of both feedstock types. In particular for hardwood cultivation the long rotation period and the discount rate result in high discounted land lease costs. Escalante (2014) gives land lease prices for different regions in the USA ranging from 65 $/ha up to 201 $/ha. Since land lease prices are likely to decrease due to subsidies or increase due to competition for land a range in the land lease costs between 50% and 150% of the original value will be tested.

The indirect costs in the investment costs are calculated as 60% of the installed equipment costs. While this is in line with literature of the NREL this high percentage causes the indirect costs to have a significant effect on the equivalent annual costs. Pirraglia et al. (2013) utilized a lower value for the indirect costs of 24%. Lowering the indirect costs from 60% to 30% of the installed equipment costs would result in an average TCI decrease of 17% for all conversion technologies. The TCI of all technologies will therefore be decreased and increased by 20%. The effect of this change is partly similar to changing the EAC. However changing the EAC has no effect on the operational costs, while changing the total capital investment does.

The GHG emissions in electricity production strongly depend on the primary energy source used for electricity generation. In the USA the average GHG emissions of different regions ranges from 250 g CO_2-eq/kWh to 860 g CO_2-eq/kWh (EPA, 2014a) and therefore the GHG emissions of electricity generation are decreased and increased by 50%.

The retail prices for fossil fuels have a high volatility (EIA, 2015g), making it impossible to accurately predict future fossil fuel prices. Since this thesis has based the production costs of fossil fuels on the retail prices of the fuels, it is uncertain how the GHG abatement costs will change in the near future. An analysis will therefore be performed on the sensitivity of the GHG abatement costs of all configurations to changes in the reference fossil fuel costs.

5. Results

The presentation of the results of the costs and GHG emissions are divided into three parts, cultivation and harvesting, transport and processing. The cultivation, harvesting and transport results are represented based on the energy content of the used biomass, while the processing results are based on the energy content of the produced bioenergy. The costs and GHG emissions per tonne are converted into costs and GHG emissions per GJ biomass using the HHV of loblolly pine and hardwood in Table 1.

5.1 Cultivation and harvesting

The non-discounted total cost of loblolly pine cultivation and harvesting was calculated to be 13,625$ per hectare, while the discounted costs were 5,819$ per hectare. Since the largest costs occur in the harvesting years, in this case years 14, 20 and 25, these costs are lowered significantly by the discount rate. The non-discounted harvested yield over the complete rotation is 700 tonne/ha with a discounted value of 174 tonne/ha. The discounted cultivation costs of loblolly pine are 20.66 $/tonne or an equivalent of 1.93 $/GJ biomass. The discounted harvest costs are 12.76 $/tonne which is equal to 1.19 $/GJ biomass. While the harvesting costs of loblolly pine account of 54% of the non-discounted cultivation and harvesting costs it only accounts for 38% of the discounted cultivation and harvesting costs.

Due to the long rotation period of hardwood the effect of the discount rate at the end of the rotation becomes very large. At the selected discount rate of 6.5% and a rotation period of 50 years, the discount factor becomes 1/23 at the end of the rotation period. Since the yield is obtained at the end of the rotation the non-discounted yield of 208 tonne/ha results in a discounted yield of 8.9 green tonne/ha. In the modelled natural hardwood scenario the discounted cultivation costs are 270 $/tonne, equal to 25.81 $/GJ biomass. The land lease costs are responsible for the majority of the cultivation costs. The harvesting costs for natural hardwood, which take place in year 50, are 11.83 $/tonne, or 1.13 $/GJ biomass.

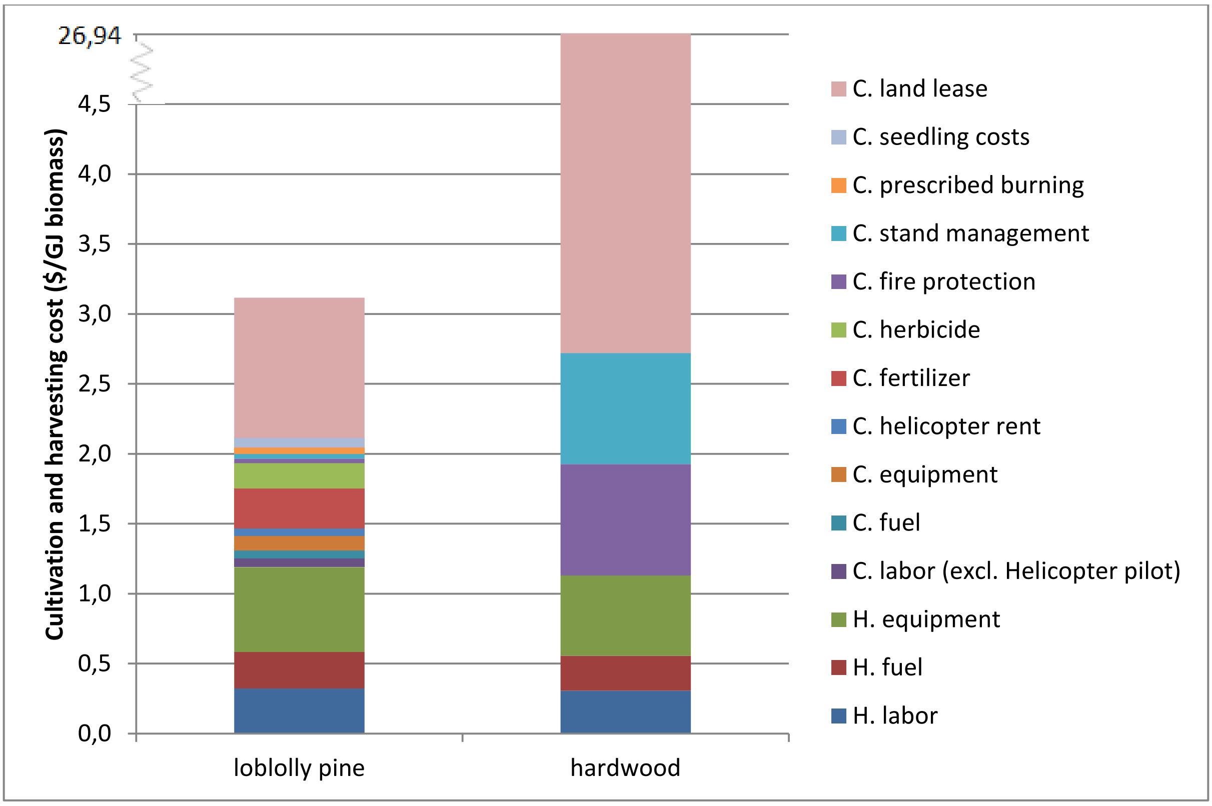

Figure 8 Cultivation costs (CC) and harvesting costs (HC) of loblolly pine and hardwood.

The GHG emissions of Loblolly pine cultivation consist of the combined emissions of used fertilizers, herbicides and diesel. The total GHG emissions of herbicides are 230 kg CO_2-eq/ha, the fertilizer GHG emissions are 8,641 kg CO_2-eq/ha, and the diesel emissions are 453 kg CO_2-eq/ha. The overall emissions of Loblolly pine cultivation are 1,242 g CO_2-eq/GJ biomass. Furthermore, the loblolly pine harvesting emissions from diesel consumption is 664 g CO_2-eq/GJ biomass.

Since this research has assumed limited operations in the cultivation phase of natural hardwood no GHG emissions are emitted during this stage. The total GHG emissions in hardwood harvesting are 1,661 kg CO_2-eq/ha. Transforming these GHG emissions gives 766 g CO_2-eq/GJ biomass.

The same harvesting equipment and equipment time is assumed per harvest for both loblolly pine harvesting and hardwood harvesting, yet the GHG emissions for hardwood are slightly higher due to the lower average energy content per harvest.

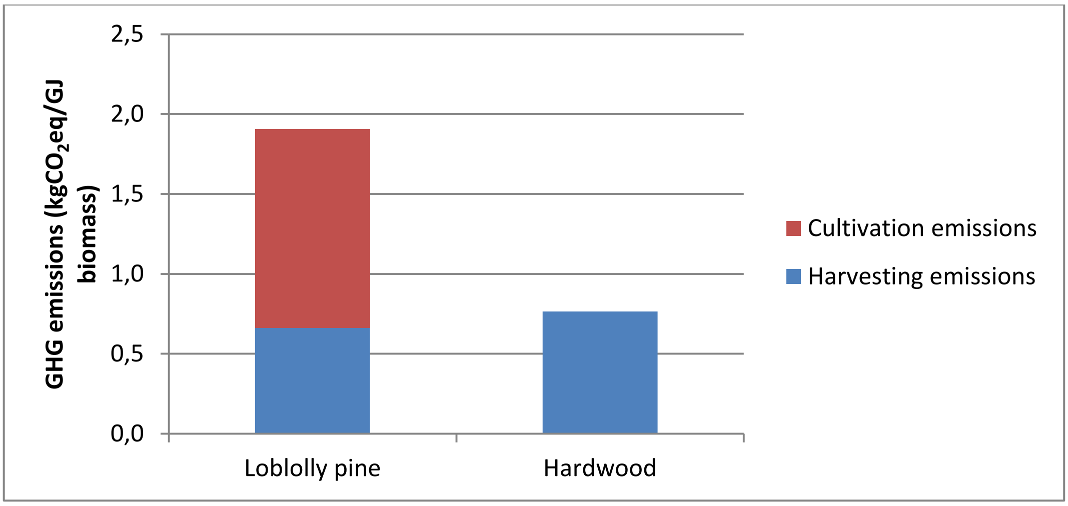

Figure 9 GHG emissions in biomass cultivation (CE) and harvesting (HE).

5.2 Transport

Based on the moisture content of loblolly pine and hardwood, the green biomass weight for a biomass to bioenergy conversion plant is calculated. Since all conversion plants are set to have a capacity of 2000 dry tonne per day, the green biomass input weight for all conversion plants is the same, namely, 1,272,727 green tonne Loblolly pine, or 1,320,754 wet tonne hardwood. Using the input data, the calculated average transport distance for Loblolly pine is 10.1 km and for natural hardwood it is 26.8 km. The difference in transport distance is the result of the yield values, which is 6.7 times higher for Loblolly pine than for natural hardwood.

The DFC of loblolly pine and hardwood, expressed in costs per tonne, is equal for both biomass types as described in chapter 4. Due to the difference in heating value of loblolly pine and hardwood, the DFC per GJ transported biomass however differ, resulting in slightly lower distance fixed costs for Loblolly pine. A more significant difference appears in the DVC of the biomass types due to the larger transport distance of hardwood.

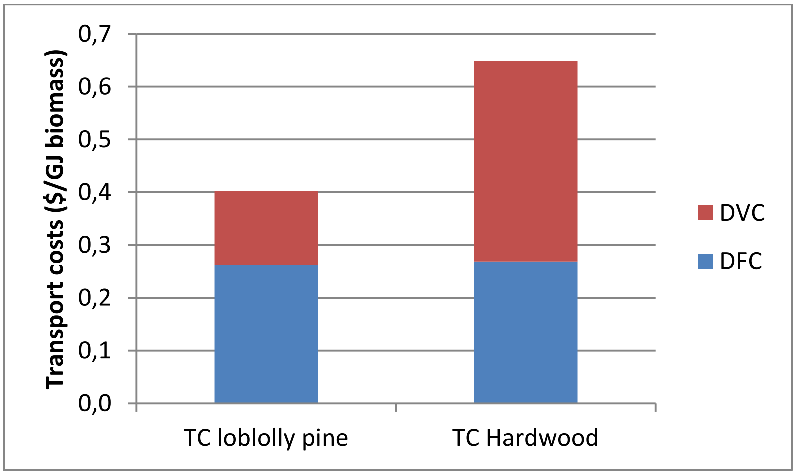

Figure 10 Biomass transport costs (TC) for loblolly pine and hardwood.

Similar to the DVC of biomass transport, the GHG emissions of biomass transport depend on the average transport distance. Since no distance independent GHG emissions are added for biomass transport the ratio between the GHG emissions of both biomass types is the same as the ratio between the DVC values.

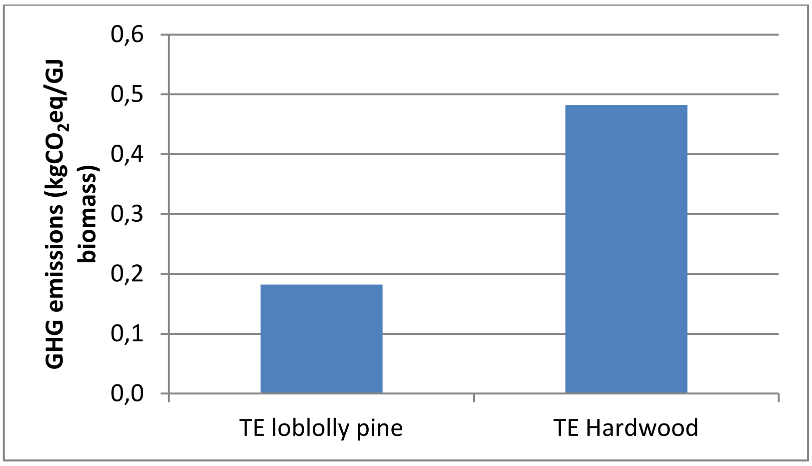

Figure 11 Biomass transport GHG emissions (TE) for loblolly pine and hardwood.

5.3 Processing

5.3.1 Annual processing costs and conversion efficiency

The conversion plants using Loblolly pine as feedstock show small differences in the total investment cost compared to the conversion plants using hardwood feedstock. For the pelleting and TOP process factories the lower moisture content in Loblolly pine requires less biomass to be used as drying fuel, resulting in slightly larger equipment scales for most components. For fermentation both configurations have the same investment cost since no drying takes place in the pretreatment of biomass, whereas the pyrolysis and the combined gasification and FT configurations using hardwood have higher investment costs due to the larger dryer scale. Similar to the investment costs, small differences have been observed in the total annual operating costs of the configurations using loblolly pine and hardwood. Where the labor costs are independent of the biomass feedstock type this is not case for the maintenance costs, insurance and taxes, which all depend on the total capital investment.

Following the calculation for the annual investment costs and operational costs, the conversion efficiency of all configurations has been determined using the energy content of the biomass feedstock and the calculated annual bioenergy production (see 18). For loblolly pine the energy content of the biomass feedstock input is 13.65 PJ, while the energy content of the hardwood is 13.81 PJ. For all configurations, higher conversion efficiency is observed when loblolly pine is used as feedstock. For the pelleting and TOP process configurations the higher conversion efficiency is the result of a lower biomass demand for drying and the lower energy content of the biomass feedstock input. For the fermentation process a higher conversion efficiency is caused by a higher conversion yield used from Daystar et al. (2013). The pyrolysis and the combined gasification and FT configuration using loblolly pine as feedstock produce similar amounts of bioenergy as the hardwood configurations, yet the lower energy content of the biomass feedstock input results in a higher conversion efficiency for the loblolly pine configurations.

Table 18 Annual bioenergy production and conversion efficieny per configuration.

	Loblolly pine		hardwood	
Conversion technology	bioenergy production (GJ/year)	conversion efficiency	bioenergy production (GJ/year)	conversion efficiency
Pelleting	11,702,646	85.7%	11,717,829	84.8%
TOP process	10,331,149	75.7%	10,317,441	74.7%
Fermentation	5,433,120	39.8%	5,237,610	37.9%
Gasification+FT	5,727,746	42.0%	5,729,627	41.5%
Pyrolysis	8,221,975	60.2%	8,221,975	59.5%

5.3.2 Bioenergy processing costs

The annual processing costs for each of the methods and steps is divided by the annual bioenergy production in Table 18 to obtain the processing costs per GJ bioenergy (see Figure 12). The main contributor in the processing costs of fermentation, combined gasification and FT, and pyrolysis are equivalent to the annual costs of the capital investment. While the total equivalent annual costs for all fermentation and pyrolysis configurations are comparable, with values between $98 million and $103 million, the EAC per produced GJ bioenergy is significantly higher due to the lower annual bioenergy production of fermentation.

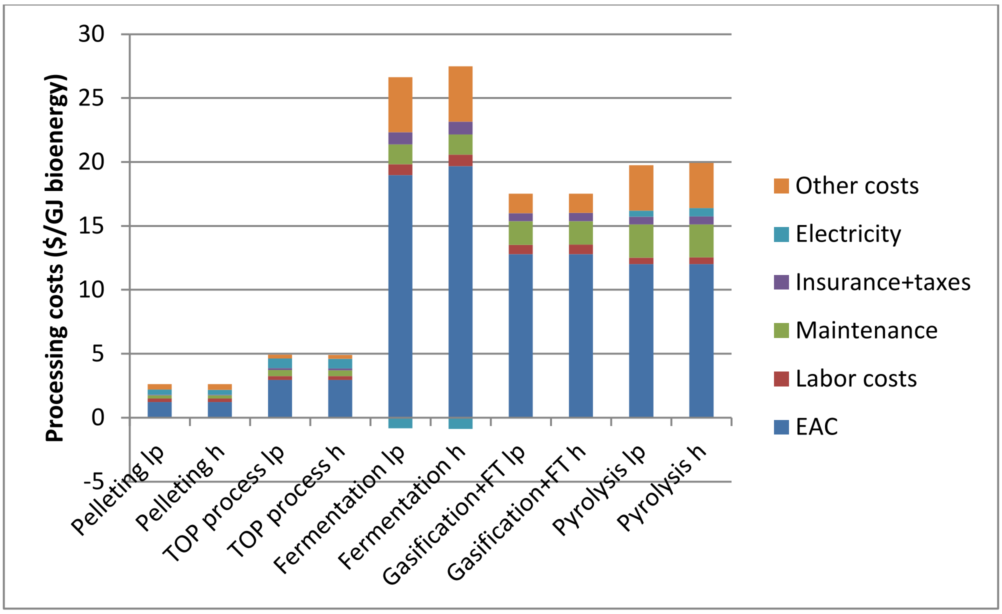

Figure 12 Biomass processing costs for all loblolly pine (lp) and hardwood (h) configurations.

Only small differences are found in the GHG emissions of biomass processing due to the electricity consumption of the pelleting and TOP process configurations using loblolly pine and hardwood. The configurations using hardwood require more electricity for biomass drying in the pretreatment due to the higher moisture content of hardwood, but the configurations using loblolly pine require more electricity for the remaining processes. The resulting GHG emissions per GJ bioenergy for the pelleting and TOP process configurations using loblolly pine are both less than 1% higher than for the hardwood configurations. For both fermentation configurations small GHG emissions have been observed in biomass processing of 26 and 29 g CO_2-eq/GJ for loblolly pine and hardwood respectively. Since the modeled gasification and FT technology is capable of providing all necessary energy, no energy needs to be purchased and the GHG emissions for this conversion technology are therefore zero. In the GHG emissions of the loblolly pine and hardwood pyrolysis configurations, a larger difference is calculated, due to the lower heat requirement for loblolly pine drying. A portion of the heat from char combustion can thus be used for electricity generation, resulting in less GHG emissions from purchased electricity. The resulting processing GHG emissions of all configurations can be seen in Figure 13.

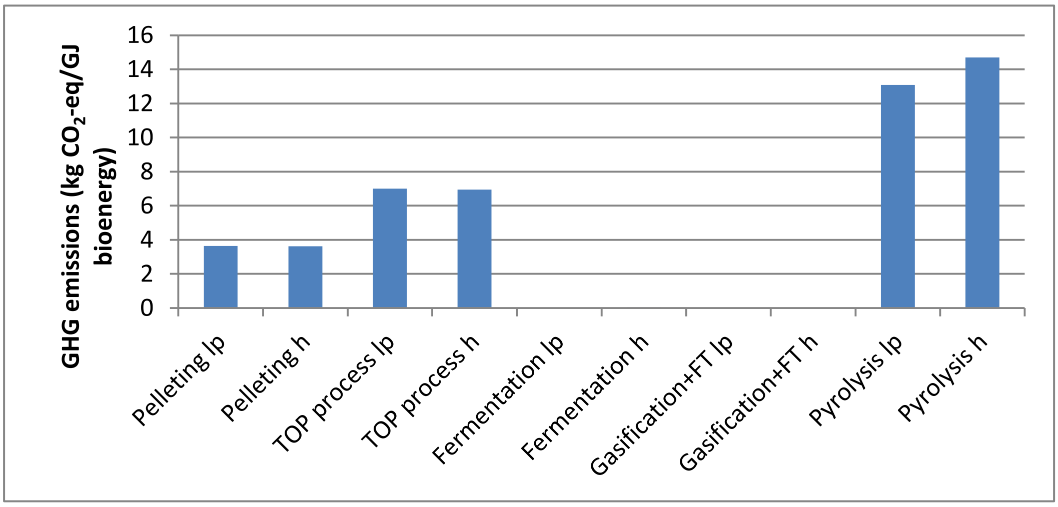

Figure 13 GHG emissions in bioenergy production from loblolly pine (lp) and hardwood (h).

5.4 Total costs and emissions

The costs of all processes in the bioenergy supply chains are combined in Figure 14 using the annual bioenergy production values and the conversion efficiencies in Table 18. For the hardwood configurations the high cultivation costs represent a large share of the total supply chain costs. In particular for hardwood fermentation and combined gasification and FT the lower conversion efficiency of the processing technologies result in high cultivation costs. The transport costs and the harvesting costs only represent a small share of the total supply chain costs in all configurations. Figure 14 also shows the costs of the fossil fuels which the bioenergy can potentially replace. On the right side of each two configurations using the same conversion technology, the reference fossil fuel production costs are given. For pellets and TOPs the reference fossil fuel is bituminous coal, for ethanol from fermentation the reference fossil fuel is motor gasoline, and for liquid bioenergy from FT and pyrolysis a mix of motor gasoline and diesel is used as reference. In the combined gasification and FT configurations 61% of the produced bioenergy is FT diesel, and the remaining 39% is FT gasoline. In the pyrolysis configurations 52% of the bioenergy is diesel, and 48% is gasoline. For both conversion technologies the composition is independent of the used feedstock.

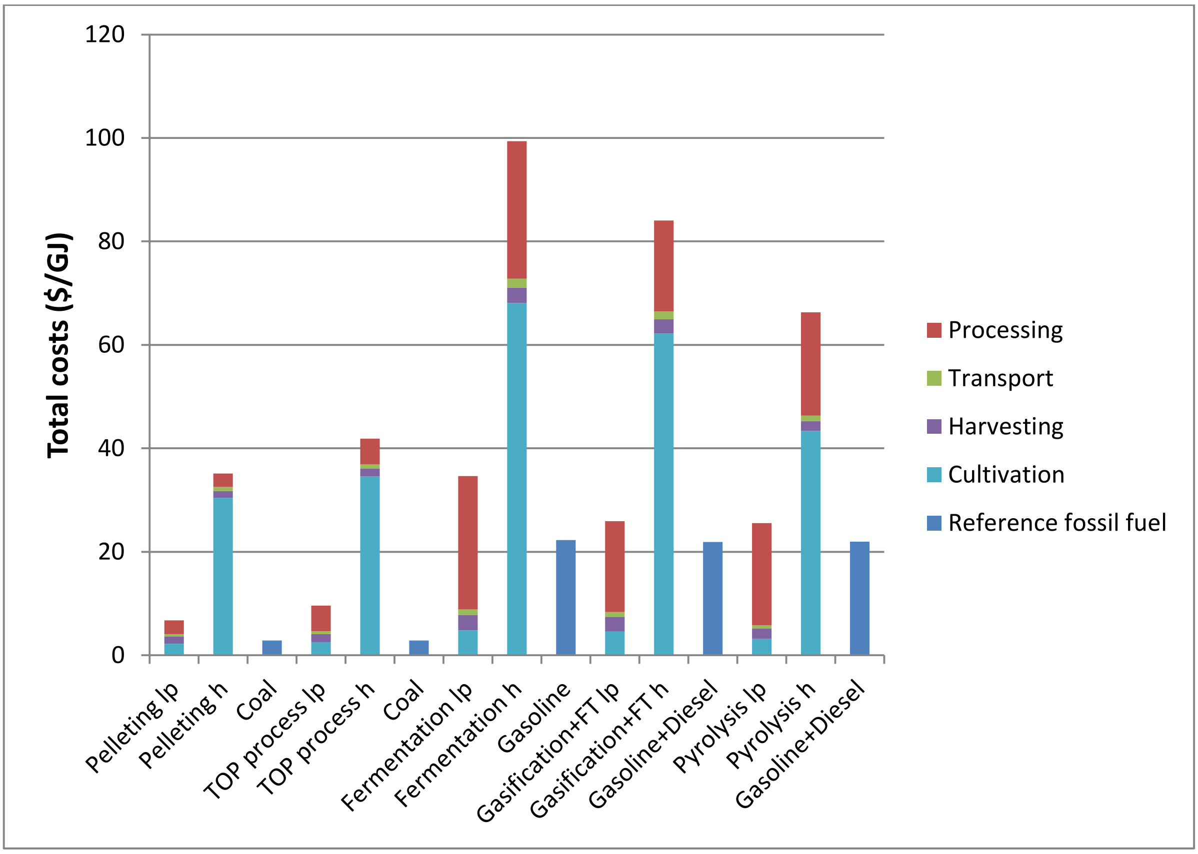

Figure 14 Total supply chain costs (SCC) for configurations using loblolly pine (lp) and hardwood (h), and the production costs of the reference fossil fuels.

In Figure 15, the total supply chain emissions of all configurations are shown. The hardwood fermentation and combined gasification and FT produce the lowest GHG emissions per GJ bioenergy output. Even though both of these technologies show lower conversion efficiencies, the absence of cultivation emissions and the low processing emissions result in lower emissions than the other configurations. The GHG emissions of the fossil fuel, or fossil fuel mix, which can be substituted by the bioenergy produced by each configuration is shown next to each two configurations using the same conversion technology.

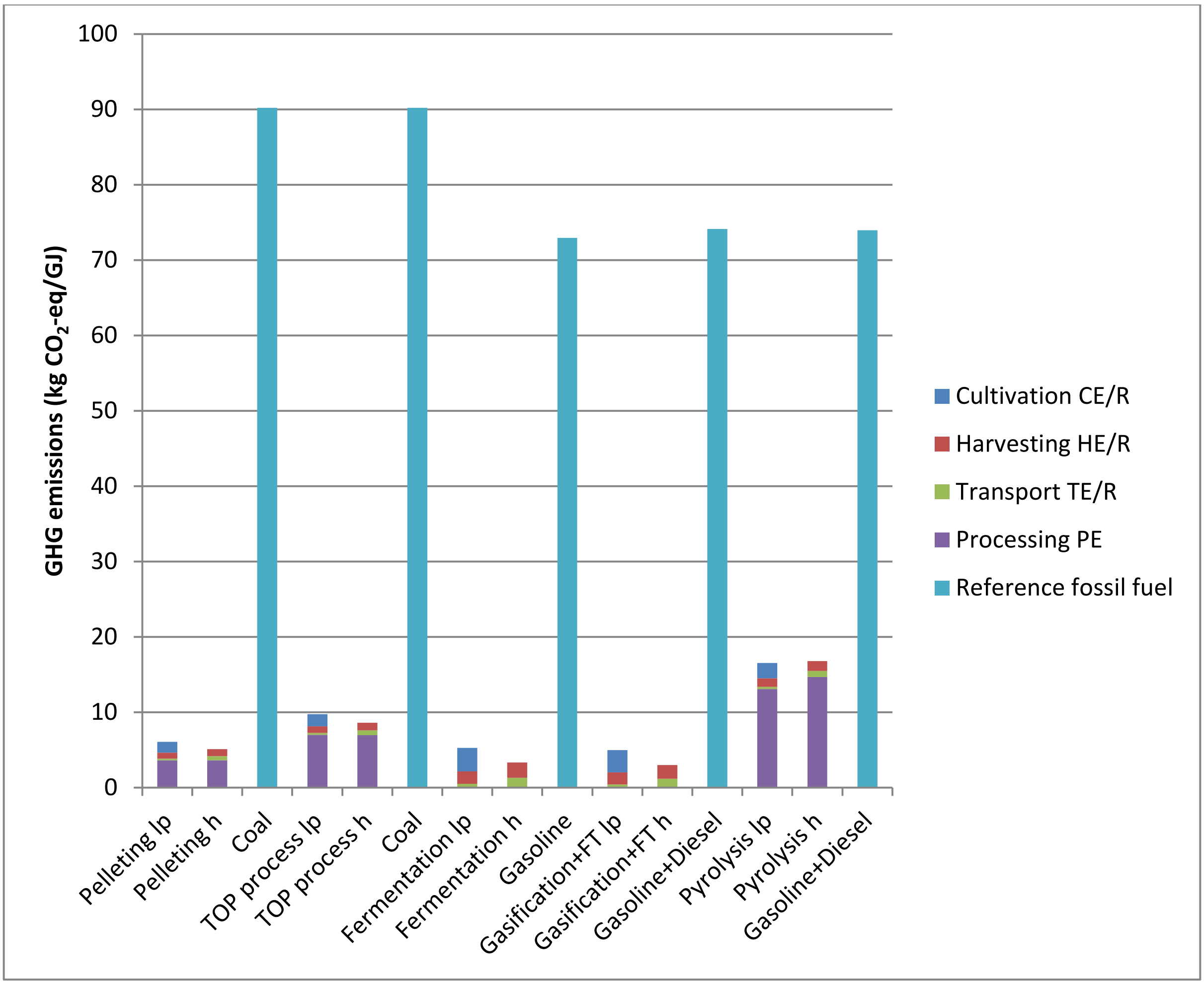

Figure 15 Total supply chain GHG emissions (SCE) for all configurations using loblolly pine (lp) and hardwood (h), and for the reference fossil fuels

In Figure 16 the GHG emissions of the bioenergy supply chains are expressed in GHG emissions per tonne dry biomass input. By comparing the GHG emissions in the conversion of one dry tonne biomass to the GHG emissions of its reference fossil fuel with the same energy content the GHG reduction per dry tonne biomass is calculated. It can be observed that the highest GHG emission reduction can be achieved by converting biomass into bioenergy through pelleting, followed by the conversion through the TOP process. Even though the conversion of one tonne biomass through pyrolysis produces the most GHG emissions per tonne biomass, it has the highest GHG emission reduction potential of all conversion technologies producing liquid bioenergy.

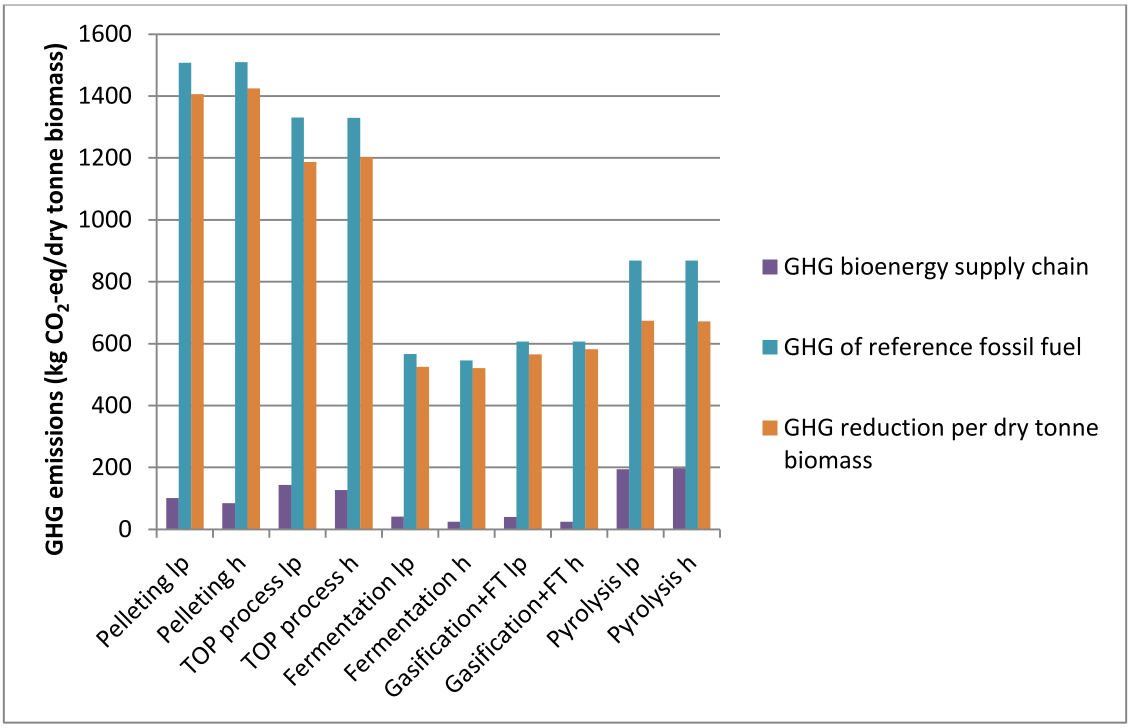

Figure 16 GHG emissions in the conversion of 1 dry tonne biomass, compared to the GHG emissions in the reference fossil fuel.

The GHG reduction potential of all configurations can be seen in Figure 16. The additional costs in using bioenergy instead of the reference fossil fuel have been divided by the avoided GHG emissions from the use of bioenergy instead of the reference fossil fuel to find the abatement costs, as can be seen in Figure 17. For all configurations using hardwood as feedstock, the costs per tonne CO_2-eq avoided are high, due to the high costs of the bioenergy compared to the reference fossil fuels. As depicted in Figure 16 the GHG reduction per tonne biomass was second highest for the TOP process conversion technology. When looking at the GHG emissions reduction costs the TOP process however performs less good compared to the other conversion technologies due to the high price difference between TOPs and its reference fossil fuel coal. The configurations using fermentation show the highest GHG reduction costs, which is the result of both a high supply chain cost, and a lower GHG emission reduction of the supply chain compared to the fossil fuel gasoline.

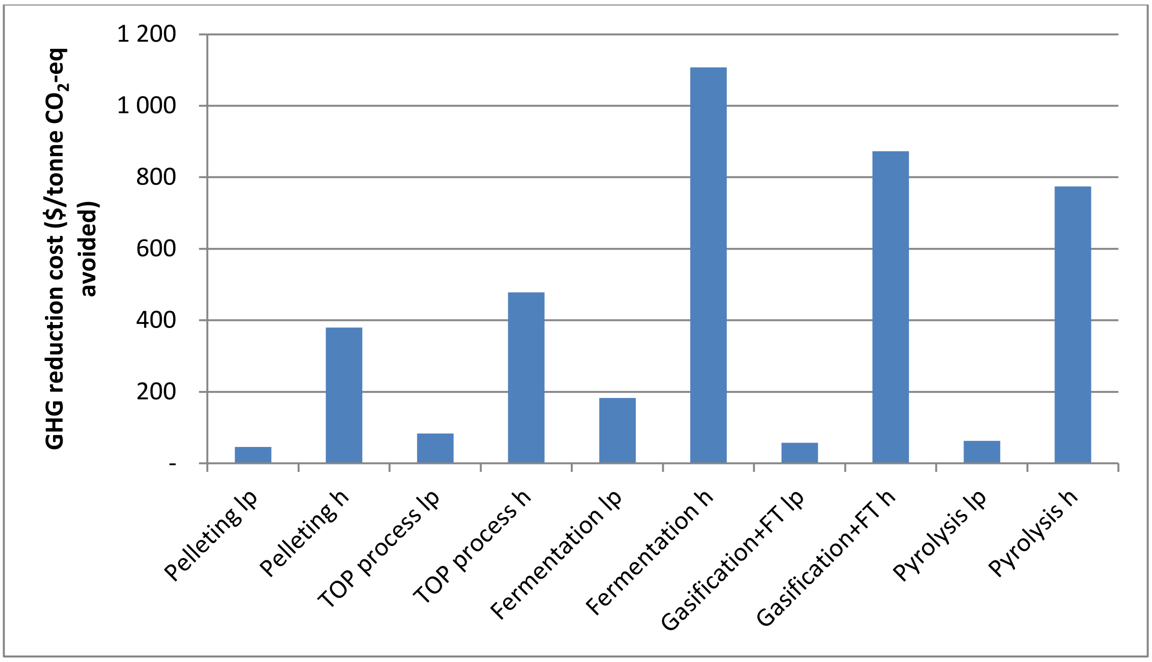

Figure 17 Costs per tonne CO2-eq avoided for all configurations.

5.5 Sensitivity

The sensitivity of the selected parameters on the bioenergy costs of all configurations is shown in Figure 18, while the sensitivity of the parameters on the GHG emissions is shown in Figure 19.

The biomass yield shows to have a strong effect on the bioenergy costs of all configurations. In particular the costs of the configurations using hardwood as feedstock are sensitive to biomass yield changes, due to the large share of the cultivation costs in the total supply chain costs of these configurations.

In the pelleting, TOP process and pyrolysis configurations a relatively small sensitivity of the supply chain emissions to the biomass yield is observed. In these configurations the largest share of the supply chain emissions come from the processing of biomass into bioenergy, which is not affected by changes in the biomass yield.

The selected discount rate in the feedstock cultivation process has a strong influence on the bioenergy costs of the configurations using hardwood. Similar to changes in the biomass yield this parameter has a large influence on the supply chain costs of hardwood configurations due to the large share of the cultivation costs in these configurations. The long rotation period of hardwood compared to loblolly pine amplifies the sensitivity of the hardwood configurations to the discount rate.

Of all modelled configurations only the loblolly pine configurations applying gasification and FT, fermentation and pyrolysis show a high sensitivity to changes in the EAC. The costs of bioenergy produced by these configurations largely depend on the processing costs, which is directly affected by changing the EAC.

Changes in the moisture content of biomass have a large effect on the costs of the cultivation, harvesting and transport processes. For loblolly pine the modeled yield is the green yield, and thus the dry yield depends on the green yield and the moisture content. For the hardwood the modeled yield is however the dry yield, meaning that the moisture content has no effect on the dry yield. This does not matter if the moisture content is not changed, however in the sensitivity analysis it can be seen that the hardwood configurations are not sensitive to changes in the moisture content.

Since a change in the moisture content of biomass influences the dry biomass yield of Loblolly pine configurations in the model, it will change the green biomass demand of these configurations. A change in the moisture content of biomass at the same time changes the drying process in several of the configurations, but the influence on the total costs of this effect is smaller than the change in cultivation, harvesting and transport costs. For the hardwood configurations the modelled dry biomass yield is independent of the moisture content. The changes which are observed in hardwood configurations due to moisture content changes, are the effects of moisture changes on the drying process of these configurations.

In the model changes in the moisture content has an influence on the cultivation and harvesting emissions of the loblolly pine configurations, while it has no influence on the cultivation and harvesting emissions of the hardwood configurations. It can however be observed that the fermentation and gasification configurations are sensitive to moisture content changes, which is caused by the large share of the transport emissions in the supply chain emissions.

The hardwood configurations in this thesis are more sensitive to changes in the land lease costs than the loblolly pine configurations. This is the result of both the lower yield, and the effect of the discount rate with a long rotation period.

As stated before, a change in the total capital investment is partly similar to a change in the EAC. In Figure 18 it can be seen that the sensitivity of the supply chain costs of all configurations to changes in the total capital investment and in the EAC are almost equal, due to the large share of the EAC in the processing costs of all configurations (see Figure 12).

In Figure 15 it has been shown that the emissions in the pelleting, TOP process and pyrolysis configurations mainly come from the processing of biomass into bioenergy. In the processing of the pelleting and TOP process configurations, electricity consumption is responsible for all emissions, resulting in a high sensitivity to changes in the GHG emissions of electricity. In the pyrolysis processing the GHG emissions are the result of both the electricity consumption and the natural gas consumption.

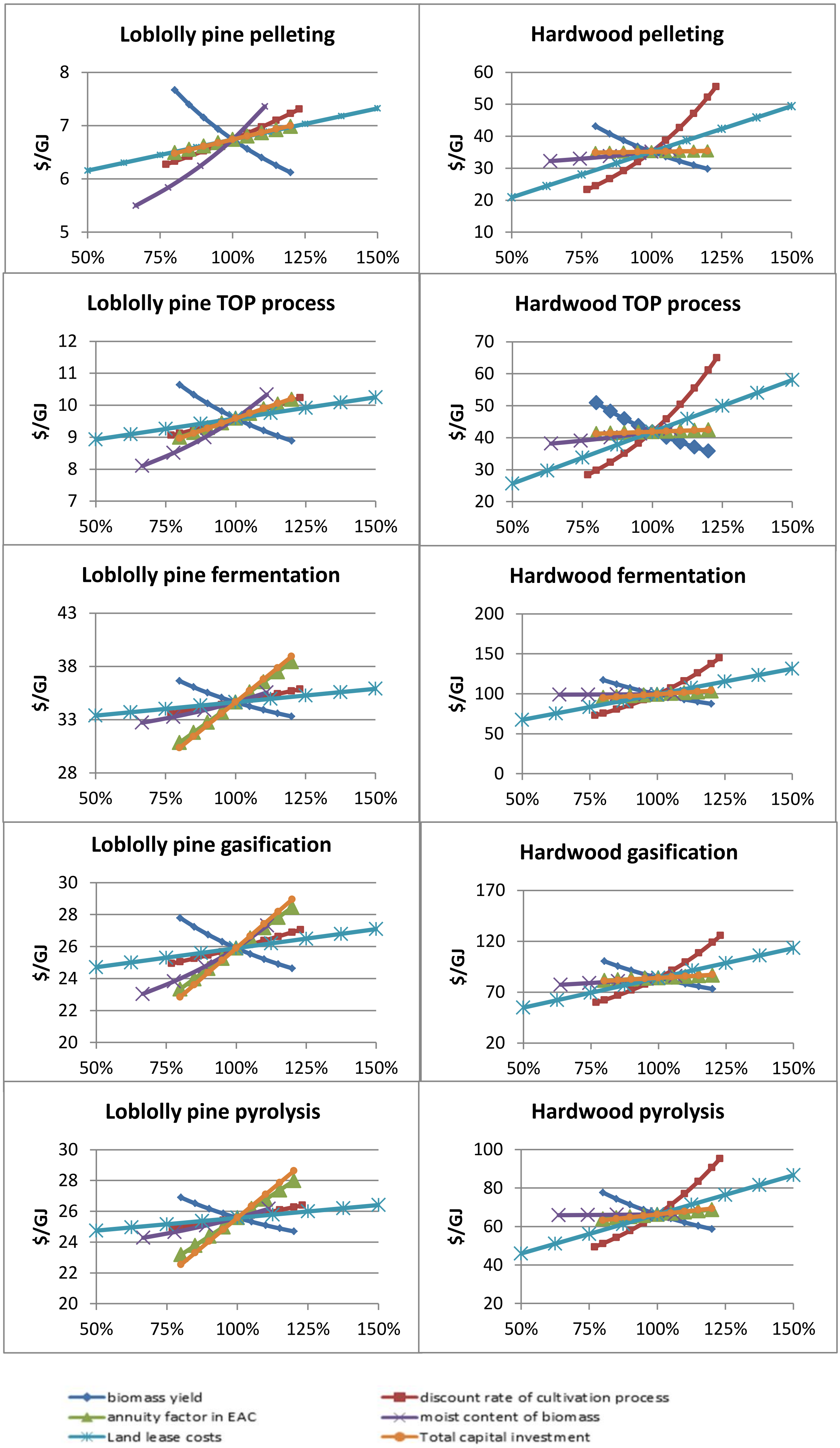

Figure 18 Sensitivity analysis on the supply chain costs of all configurations.

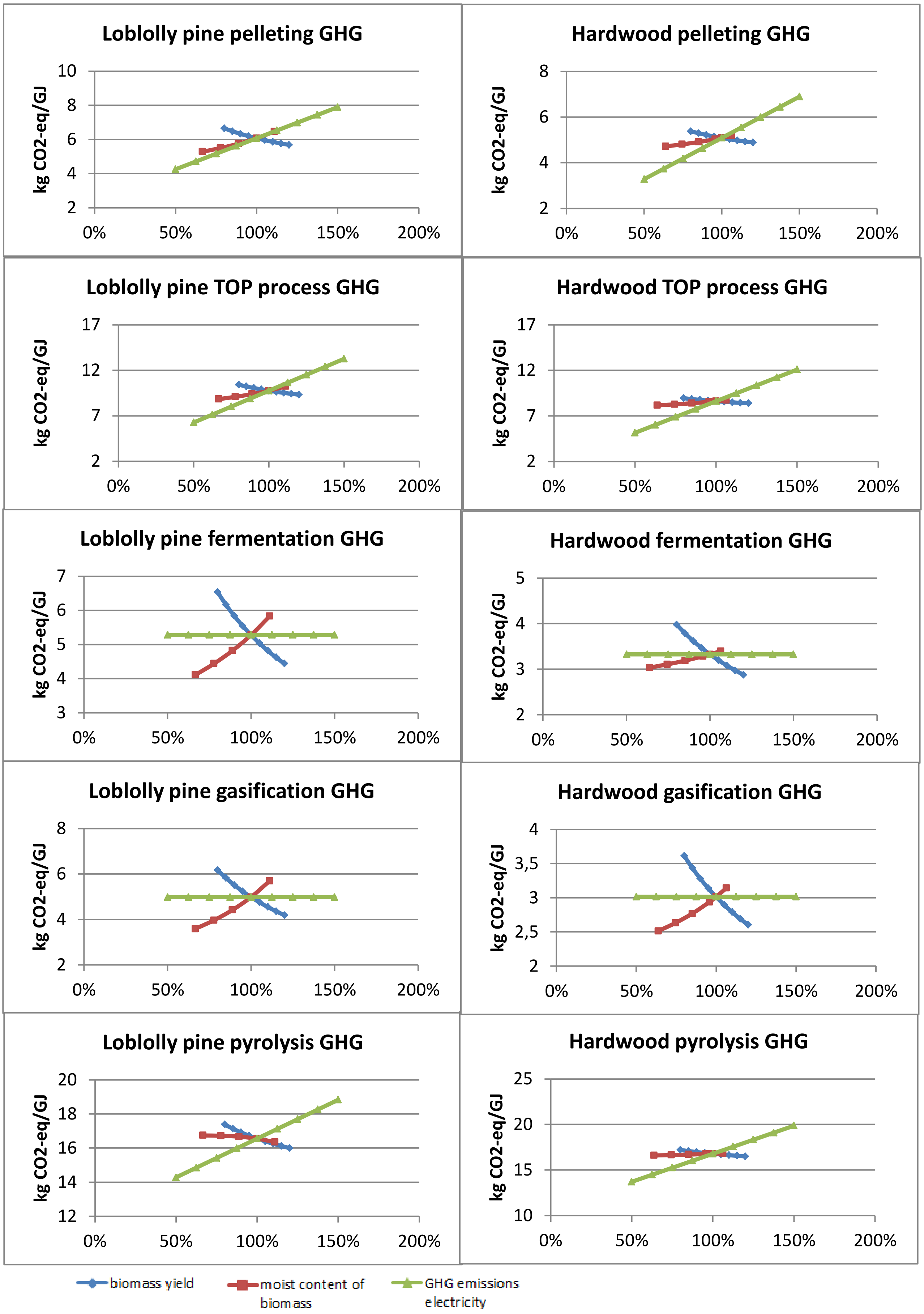

Figure 19 Sensitivity analysis on the supply chain GHG emissions of all configurations.

In Figure 20 the sensitivity of the abatement cost of each configuration, to changes in the reference fossil fuels. It can be seen that the configurations producing possible substitutes for coal are not sensitive to fossil fuel price changes. The low price of the reference fossil fuels for these configurations result in small changes in the difference between the production costs of the bioenergy and the reference fuel, leading to small changes in the abatement costs. Furthermore, it can be seen that the Loblolly pine combined gasification and FT, and the Loblolly pine pyrolysis configurations will lead to negative abatement costs if the costs of the reference fossil fuels increase by approximately 15-20%. The abatement cost become negative when the costs of the reference fossil fuels are higher than the costs of the substitute bioenergy.

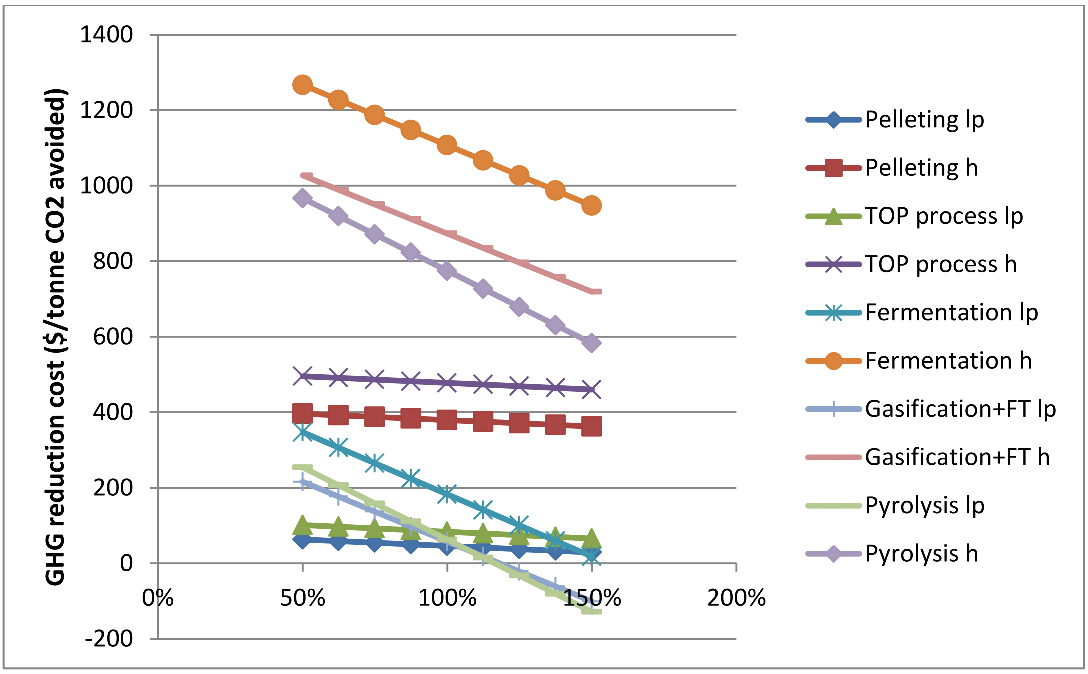

Figure 20 Sensitivity analysis for the GHG emission reduction cost of all configurations. The production cost of the reference fossil fuel is varied between 50% and 150% of the original value.

6. Discussion

The objective of this study was to determine the costs and GHG emissions of different - biomass to bioenergy - conversion configurations in the Southeastern USA. To compare the configurations, an excel model was made allowing to combine a large set of input parameters from different studies. In order to make a valid comparison between the conversion chains, this research focused to use as similar assumptions as possible for all configurations. The costs and the GHG emissions calculations of the produced bioenergy are based on a broad range of parameters. Due to the dependency on a large amount of parameters and assumptions the results should be considered carefully. However, by applying the same assumptions and parameters to all configurations, this thesis is able to provide an indication of the costs and GHG emissions of the configurations relative to each other.

This thesis has attempted to model all parameters which have the largest influence on the costs and the GHG emissions of the different supply chains. It is however likely that many other parameters have an effect on the supply chain performance, which have not been taken into consideration. It is therefore expected that the actual costs and GHG emissions are higher than the values found in this research. One of the parameters which has not been taken into consideration in this thesis is land-use change. As stated in the introduction, the declining wood demand in the Southeastern USA region, and increasing biomass yield, could allow for bioenergy crop production without land-use change. It is however not likely that a new conversion plant of the scale selected in this research would not lead to land-use changes. Applying land use change could reduce the GHG emission reduction potential of the bioenergy due to GHG emissions from land conversion (van der Hilst, 2012). Another parameter which is excluded from this project, but may have a large effect on its outcome, is the carbon debt. For loblolly pine, under the assumptions made in this research, carbon debt would have a relatively small effect since the biomass is first planted and cultivated before it is harvested. For natural hardwood, the carbon debt will however have a much larger effect. Furthermore, the transport of bioenergy after conversion was not included in this thesis. Adding this transport could have a considerable effect on the GHG emissions of the bioenergy supply chains. This counts in particular for bioenergy types which have a lower energy density than the fossil fuel which they can substitute.

In the introduction of this thesis it has been assumed that bioenergy is considered carbon neutral since the emissions from bioenergy combustion have previously been absorbed by biomass during growth. This assumption however has received increasing criticism. Changing this assumption would have a large influence on the results of this thesis.

In this thesis, the characteristics of the produced bioenergy has not been considered. For instance TOPs have some preferable characteristics over pellets (e.g. TOPs are hydrophobic, and have an higher energy density than pellets). However, these characteristics are not reflected in the calculated costs and GHG emissions of the bioenergy. Therefore, the choice for an bioenergy supply chain can not be made on only the results of this thesis.

The large amount of data, which is necessary in order to compare bioenergy configurations to fossil fuels, is one of the main limitations of this research. Due to a time constraint, only a limited amount of possible feedstock types and conversion technologies were taken into consideration. As mentioned in chapter 2, different groups of feedstock could be used for bioenergy production, but are nevertheless not incorporated in this research. This does not influence the costs and GHG emissions of the modelled configurations, but it ignores alternative configurations which may have a higher GHG emission reduction potential or lower supply chain costs. In addition only a limited amount of management intensities and supply chain structures have been modelled.

During this research, it appeared difficult to combine data from different literature. For instance, the planting density has a great effect on the obtained biomass yield, but also on the costs and GHG emissions of the processes following biomass cultivation. It is however not clear how these factors are affected by changes in the planting density. This thesis aimed to model the influence of each parameter on other parameters. The cohesion between parameters are however estimates, and further research is thus required to improve or verify the coherence between all parameters.

The fraction of land usable for biomass production, which has been assumed in this research, has appeared to be much higher than values used in other literature. While in this thesis, a fraction of 90% has been assumed, Wright and Brown (2007b) apply a fraction of 60%. Using this higher fraction for usable land has a significant effect on the transport distance. For instance using a fraction of 45% instead of 90% would lead to doubling of the land size, and a 41% larger average transport distance.

For this research, the production prices of fossil fuels are calculated as a percentage of the selling price. While this is an arguable method to calculate the production price it was necessary since no specific data on production costs was found. A justification for this method is that the production costs largely depend on the crude oil costs, and that the selling price largely depends on the production costs.

This research has found cost data for all configurations and has used assumptions in order to ensure that the configurations can be compared. However, due to the large amount of used sources, the reliability of the data is expected to be low. Care was taken that the calculations of the different configurations rely on similar assumptions, but it appeared to be difficult to ensure this. While the sensitivity analysis in Figures 18 does not show very large changes in the total costs of the supply chains, Figure 20 shows that small changes in the supply chain costs or in the reference fossil fuel costs can have a large influence on the abatement cost of bioenergy. This shows that the results for the GHG abatement costs found in this thesis are not robust.

While a large uncertainty exists in the comparison of bioenergy costs and fossil fuel costs, the comparison of the GHG emissions is more reliable. The GHG emissions in fossil fuel production and consumption are not as uncertain as the fossil fuel costs, allowing for a better comparison with bioenergy.

7. Conclusion

The goal of this thesis was to answer to main research question: “determine the potential economic performance and GHG emission intensity of state of the art biomass to bioenergy conversion configurations - using selected feedstock and conversion technologies- in the Southeast of the USA”. In order to answer the research question, different processes of the bioenergy conversion configurations have been modeled.

This thesis has modelled two different feedstock types to be used for bioenergy production in the Southeastern USA region. Loblolly pine has been selected since it is considered to be the best feedstock for commercial bioenergy production by many foresters in the region. The second feedstock is mixed natural hardwood, which is described by different studies for bioenergy production. The conversion technologies considered for bioenergy configurations are pelleting, TOP process, hydrolysis and fermentation, gasification and FT and pyrolysis.

The cultivation costs for loblolly pine in this research are 20.66 $/green tonne, which equals 1.93 $/GJ biomass. The cultivation costs for mixed natural hardwood are much higher than the cultivation costs of Loblolly pine. The long rotation length and the lower yield of hardwood, in combination with the discount rate result in cultivation costs of 269.93 $/green tonne, equaling 25.81 $/GJ biomass. This model has therefore found that under the used assumptions it is not economically interesting to cultivate hardwood as feedstock for biomass to bioenergy conversion. Due to the selected management practices the cultivation of hardwood however has no GHG emissions, while the cultivation of Loblolly pine leads to 1.24 kg CO2-eq/GJ biomass.

The harvesting costs of Loblolly pine is 1.19 $/GJ biomass, while the harvesting costs of hardwood are 1.13 $/GJ biomass. Since the same harvesting equipment is assumed for both feedstock types the costs and GHG emissions are comparable for both feedstocks. Both the transport costs and the transport GHG emissions in hardwood transport are higher than the costs and GHG emissions in Loblolly pine transport due to the larger transport distance. The transport costs only represent a small share of the supply chain costs of all configurations.

The processing costs of the configuration applying pelleting and TOP process are significantly lower than the other configurations. These configurations mainly benefit from lower capital investments than the other conversion technologies. At the same time the higher conversion efficiency of these configurations lead to a higher annual bioenergy production, and thus a lower costs per GJ bioenergy output. The processing of hydrolysis and fermentation, gasification and FT, and pyrolysis all have high EAC values leading to higher processing costs. For the hydrolysis and fermentation configurations the low conversion efficiency results in the highest processing costs of all configurations.

The configuration applying hydrolysis and fermentation and gasification and FT produce little or no GHG emissions since it is assumed that the conversion facilities are able to provide in their own energy demand. Of the remaining configurations the pyrolysis configurations result in the highest GHG emissions.

When the biomass produced by the different configurations is compared to the fossil fuels - which they can potentially replace - two different scenarios’ can be used. In the first scenario, it is looked what the GHG emission reduction is due to the conversion of 1 tonne biomass in different configurations. This scenario finds that the pelleting, and after the TOP process configurations, lead to the largest GHG emission reduction of approximately 1200 to 1500 kg CO_2-eq per dry tonne biomass.

The remaining conversion configurations show comparable GHG reductions, around 600 kg CO_2-eq per dry tonne biomass. In the second scenario, the cost difference between bioenergy and its fossil fuel reference is divided by the GHG emission reduction of bioenergy compared to fossil fuel, to find the GHG emission abatement cost. For the configurations using hardwood this scenario leads to high GHG emission reduction costs due to the high costs of the biomass. For the remaining loblolly pine configurations the pelleting technology leads to the lowest abatement costs.

At the moment of this thesis the loblolly pine pelleting configuration leads to the highest GHG emission reduction per dry tonne biomass converted, and in the lowest abatement costs. As shown in the sensitivity analysis it is not likely that the fermentation, gasification and pyrolysis configuration will have higher GHG emission reduction per tonne biomass converted in the near future. The GHG abatement costs could however fall below the GHG abatement costs of the pelleting configurations. In particular when fossil fuel prices increase.

This research shows that under the selected conditions no bioenergy configuration can produce bioenergy at the same cost as fossil fuel production. However, due to the uncertainty of the modeled parameters it is very well possible that bioenergy production at competitive prices will be possible in the near future. It is therefore recommended to companies and investors to further investigate the costs and GHG emissions in bioenergy production.

While this research is able to give indications of the costs and GHG emissions of bioenergy compared to the fossil fuels, it is recommended that future research takes place to expand the model. By incorporating more feedstocks and conversion technologies a better choice in bioenergy supply chain can be made. Furthermore, it is recommended that the parameters applied in this research are verified and possibly updated.

This thesis shows the sensitivity of the success of bioenergy production to uncertainties. It is therefore recommended to policymakers that as much uncertainty as possible is avoided. For instance future tax regulations and financial incentives could have a large effect on the costs of bioenergy production, and could therefore determine if companies dare to invest in bioenergy production.

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Appendix A: Loblolly pine yield values

Table 19 Different Loblolly pine yield values from literature

Author	publication Year	yield	units	notes
Borders and Bailey	2001	29.0	green tonne/ha/year	average over 9 years
Scott and Tiarks	2008	24.6	green tonne/ha/year	average over 22 years
Miller et al.	2003	14.3	green tonne/ha/year	
Dickens and Jackson	2011	28.9	green tonne/ha/year	
Jokela et al.	2004	12.0	green tonne/ha/year	without thinning, average over 15 years
Antony et al.	2011	22.7	green tonne/ha/year	
Zhao and Kane	2012	20.4	green tonne/ha/year	average over 15 years
Allen et al.	2005	16.0	dry tonne/ha/year	possible on many sites across the southern United States
Gonzalez et al.	2011	15.5	dry tonne/ha/year	

Appendix B: Input data labor and helicopter

Table 20 Labor costs and helicopter time costs for biomass cultivation and harvesting

function	hourly wage ($/hour)	hourly cost* ($/hour)
forested land manager[a]	28.88	37.54
Logging[a]	32.37	42.08
skidder operator[a,b]	17.23	22.40
helicopter time[c]		1302.80

aMean hourly wage for ‘Foresters’, ‘Logging’ and ‘Logging Equipment Operators’ in 2014 is obtained from www.bls.gov

bThe hourly wage for ‘Skidder Operator’ is in line with values found on http://work.chron.com/ and http://www.executivetrackers.com/.

cThe costs for helicopter time represent the hourly costs for renting a helicopter for aerial fertilizer and herbicide application based on (Buffelgrass, 2015), and updated to $$_{2014}$. The costs for helicopter time include the helicopter fuel costs.

Appendix C: Input data cultivation and harvesting equipment

Table 21 Input data for cultivation and harvesting equipment (part 1)

Machine	model	Attach type	Rated power (hp)	Life[a] (years)	R&M[b] rate	Insurance costs[c]	Purchase price
Skidder	Caterpillar 525	Grapple	175	5	90%	5%	$ 250,779
Feller buncher	Tigercat 726B	Saw	215	5	100%	4.5%	$ 279,107
Forwarder	Timberjack 1710	Knucboom	210	6	30%	4%	$ 576,517
Tractor	Tigercat S640	Plow	240	5	90%	4%	$ 235,251

a The life of the machine shows after how many years the machine should be sold. The salvage value of all equipment is 20% at the end of the equipment lifetime. The annual depreciation of equipment is then calculated by dividing the total depreciation by the lifetime of the equipment.

b The R&M rate shows how the annual repair and maintenance costs relate to the annual depreciation costs.

c The annual insurance costs are calculated as a percentage of the purchase price.

Table 22 Input data for cultivation and harvesting equipment (part 2)

Machine	Original production h[d] hour/year	Selected production h[e] hour/year	Fixed costs[f] $/hour	Lube and Oil[g] $/hour	R&M $/hour	Total costs (excl. Fuel) $/hour
Skidder	1200	3000	17.55	5.96	12.04	35.55
Feller buncher	1300	3000	19.07	6.88	14.89	40.84
Forwarder	1600	3000	33.31	6.35	7.69	47.35
Tractor	1200	3000	15.68	8.17	11.29	35.14

d The original production hours per year are obtained from Brinker et al. (2002), and are added to this table as reference.

e This research applies a higher amount of production hours for all machinery (3000 hours/year). Using the higher production hours per year is assumed to be reasonable since cultivation and harvesting take place year round.

f The fixed costs per hour are calculated by dividing the annual depreciation and the annual insurance costs by the production hours per year (Brinker et al., 2002). Since this research uses a higher amount of production hours, the fixed costs per hour decrease. For this research it is assumed that the annual depreciation of used equipment is not affected by the higher amount of production hours per year.

g The lube and oil costs for cultivation and harvesting equipment are calculated by multiplying the fuel costs by 36.8% (Brinker et al., 2002). The fuel costs are calculated by multiplying the equipment fuel consumption (Brinker et al., 2002) by the average 2014 diesel price (including tax) in Georgia. The costs of the used lube and oil are often based on the fuel costs since the factors which determine the fuel use also determine the amount of lube and oil used for the equipment.