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Life Cycle Assessment of Norwegian Bioenergy Heat and Power Systems

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Master Thesis
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Life Cycle Assessment of Norwegian Bioenergy Heat and Power Systems

Livsløpsanalyse av norske bioenergisystemer

Background

The present formidable environmental challenges require efficient energy procurement and conversion systems to direct us onto a sustainable path. Norway has a substantial and increasing standing mass of boreal forest. This offers an opportunity to pursue bioenergy as a climate mitigation option. The Norwegian government has made a call to double 2009 bioenergy (heat and power) production, from fourteen to twenty-eight Terra-Watt-hours (TWh) by 2020. There are several technological options and management strategies to convert biomass to heat and power. In this research attention will be focused on a number of permutations involving several biomass feed-stocks, comminuting strategies and energy conversion technologies. The unit based life cycle assessment (LCA) of these energy systems will then be hybridized using the input-output framework in a scenario based study that compares LCA impacts and biomass inputs to the Norwegian bioenergy sector as it is today and as it could be when this doubling of bioenergy is achieved.

The industrial ecology life-cycle analysis tool will be the core method for this research. Several boreal biomass procurement systems will be compared across a few environmental impact categories, including climate change, acidification and resource depletion. The energy produced will be heat and/or power from a small-to-medium scale district heating and/or power plant assumed to be located in Norway. Close detail to fuel properties and logistics at the different stages in the fuel chain will be essential to understanding the environmental impact differences between the bioenergy system permutations.

Aim

The main aim of this research is to assess the life cycle impacts of several boreal biomass-to-heat and/or power systems in the Norwegian context. The first stage is to perform unit process based LCAs of the bioenergy systems. By comparing several biomass feed-stocks and comminuting and conversion technologies the environmental impacts can be compared. One impact category of particular importance is climate change. In this work recent methodologies for dealing with the climate impact potential due to the biogenic carbon along with forest surface albedo effects due to deforestation which was developed by colleagues within the NTNU Industrial Ecology Programme will be applied. Significant differences are foreseen in the global warming potential (GWP) metric when comparing the differing primary and secondary biomass feedstocks. Important GWP allocation issues also need to be considered when assessing the secondary feed-stocks since the impacts should be distributed fairly across the value chain.

Once the process unit based LCAs have been constructed, these systems can be integrated with the Norwegian economy. To do so, Norway's bioenergy system will first be disaggregated into a series of sub-sectors based on mass and energy flow statistics from a recent year. Scenario base LCA can then be performed around the Norwegian bioenergy system as it presently operates today. Several future bioenergy systems can then be envisioned for achieving the goal of doubling bioenergy production in Norway. Several biomass feedstock mixes will be considered along with the most suitable combination of comminuting and conversion technologies based on results from the first stage of this research.

The analysis should include the following elements:

1) Development of life cycle inventories for the several bioenergy system permutations.
2) Life Cycle Assessment for each of the bioenergy systems studied.
3) Comparative assessment between the cases with recommendations on how to develop the most environmentally sustainable boreal bioenergy system in Norway.
4) Carryout a scenario based LCA based on Norway's bioenergy system.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

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Department of Energy and Process Engineering, February 2012.

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PREFACE

This work is the result of my master's degree at the Department of Energy and Process Engineering, Norwegian University of Science and Technology, spring 2012. I give my greatest acknowledgments to Anders Hammer Strømman and Geoffrey Guest. I am very grateful for all guidance, ideas and encouragements. I thank Geoffrey for his eyes on detail and his continuous encouragements to improve my model. I would also like to thank Ryan Bright and Francesco Cherubini for helping me understand albedo effects. I feel very glad to have been working with LCA of bioenergy systems. A great research community at the industrial ecology program has made this topic exciting.

Beverly, I am very grateful for your help. Your proofreading has been invaluable and I am impressed by your will to understand and read through this thesis.

I would like to thank all my class mates and friends throughout my five years at NTNU; you have made my five years in Trondheim the best. Lunches and coffee breaks during thesis writing have made the process enjoyable. Kaja, you and I have had the best time in our office and our talks are always the best. Peace.

Mom, Dad, Ragnhild, you will be very glad to read your names here. I thank you for that. I am also grateful for dinners, support and Bristol fun. Julian, thank you for being my rock.

ABSTRACT

This thesis assesses several value chains for bioenergy production in Norway and combines these representing two Norwegian scenarios. The environmental impacts are assessed using the methodology of life cycle assessment (LCA). A complete assessment of climate change impact has been a core task, and biogenic CO_2 emissions are accounted for throughout the value chains investigated. Surface albedo effects are included in the assessment of forest resources. In addition to global warming potential, the value chains are assessed for three other impact categories; acidification potential, particulate matter formation potential and terrestrial ecotoxicity potential. Life cycle inventories are constructed for a set of six feedstocks, seven treatment options, ten energy conversion options and three energy distribution choices. The different options are then combined to 80 feasible value chains. Transport is included throughout all the value chains. All inventories are assembled to represent Norwegian conditions. Energy flows for the different value chains investigated are found to represent the current bioenergy system, with a potential increase for each value chain towards 2020 - representing the alternative scenario. Results are generated for the individual value chains, the reference scenario and the alternative scenario.

The results show large differences between the different value chains. Energy wood and waste wood are the most beneficial feedstocks for bioenergy production, highly dependent on both the GWP_{bio} factors utilised and inclusion of surface albedo effects. Pelletising is the pre-treatment option resulting in the lowest GWP, while integrated torrefaction and pelletising results in the highest GWP. Overall, a CHP plant with electricity demand is the most advantageous conversion route. A stand-alone thermal electricity plant has the definite highest impact, mainly because of low conversion efficiency. Heat distribution shows high impacts compared to electricity and steam distribution, and the resources resulting in lower impacts is therefore recommended as

inputs for such units. Generally, handling of biogenic CO_2 emissions is of high importance. The same is the case for surface albedo effects, changing the GWP for forest resources considerably.

CHP plants are recommended for electricity production from biomass, and use of TOP, forest residues and stemwood are recommended to take place in the same conversion technology. The environmental impacts from a CHP plant is low, and TOP, forest residues and stemwood show high GWP. The GWP from energy wood, wood waste and pellets are low, and are therefore recommended for use in district heating plants. As stand-alone electricity production is not recommended, the GWP from a district heating plant is limited with the use of the mentioned resources. Pelletising is recommended for pre-treatment of Norwegian biomass because of low climate change impacts.

The Norwegian Government has put forth ambitious goals to reduce the GHG emissions substantially towards 2020 and become climate neutral by 2030. The reference scenario assessed show a GWP of 134 grams CO_2-equivalents per kWh, while the scenario for 2020 results in a climate change impact of 136 grams CO_2-equivalents per kWh. Based on this, Norwegian bioenergy can offer a means to reduce the GHG emissions towards 2020, but because of considerable GWP from biogenic CO_2 emissions, bioenergy should not be pursued for a goal of becoming climate neutral by 2030.

SAMMENDRAG

Denne masteroppgaven evaluerer flere verdikjeder for bioenergiproduksjon i Norge og kombinerer disse til å representere to scenarioer for norsk bioenergiproduksjon. Miljøpåvirkningene er evaluert ved hjelp av livsløpsanalyser (LCA). En helhetlig vurdering av klimaeffekten (GWP) fra det modellerte systemet har vært en kjerneoppgave, og biogene CO_2-utslipp er medregnet i alle steg for alle verdikjeder. Albedoeffekter er inkludert i evalueringen av klimaeffekten fra flere verdikjeder fra norsk skog. I tillegg til globalt oppvarmningspotensiale, er verdikjedenes miljøpåvirkning evaluert ved hjelp av tre andre påvirkningskategorier; forsuringspotensiale, dannelse av svevestøv og landlig økotoksisitetspotensiale. Livsløpsinventar er utformet for et sett bestående av seks råmaterialer, syv forbehandlingsmetoder, ti energikonverteringsvalg og tre energidistrubonsjonsmetoder. De forskjellige valgene er kombinert til 80 forskjellige, mulige verdikjeder Transport er inkludert for alle verdikjeder, og alt inventar er utformet for å representere norske forhold. Energistrømmer for de forskjellige verdikjedene er funnet for både et referensescenario og et alternativt scenario. Refereansescenarioet representer norske forhold i dag (2010), mens det alternative scenarioet represeterer en potensiell vekst i bioenergi mot 2020. Resultater er funnet for hver av de 80 verdikjedene, samt for både referansescenarioet og det alternative scenarioet.

Resultatene viser store forskjeller mellom verdikjedene. Energived og avfallstre er de råressursene som resulterer i lavest påvirkning, i hovedsak på grunn av GWP_{bio} faktorer og medregning av albedoeffekter. Pelletsproduksjon er den forbehandlingsmetoden som resulterer i lavest GWP, mens integrert røsting og pelletsproduksjon (TOP) resulterer i det mest signifikante oppvarmningspotensialet. En CHP-teknologi med elektrisitetsetterspørsel er den energikonverteringsteknologien som resulterer i lavest miljøpåvirkning. Frittstående

elektrisitetsproduksjon har desidert høyest påvirkning, i hovedsak på grunn av lav konverteringseffektivitet. Varmedistrubusjon viser de høyeste påvirkningene av distribusjonsmulighene, og råressursene som resulterer i lavest miljøpåvirkning er derfor anbefalt som innputt for slike enheter. Genrelt, håndtering av biogene CO_2-utslipp er særdeles viktig. Dette er også tilfelle for albedoeffekter, som endrer klimaeffekten fra skogressurser signigikant.

CHP-anlegg er anbefalt for elektrisitetsproduksjon fra biomasse, og bruk av TOP, grot og rundtømmer anbefalles for denne konverteringsteknologien. Miljøpåvirkningen fra et CHP-anlegg er lav, og TOP, grot og rundtømmer har høy klimapåvirkning. Klimapåvirkningen fra energived, avfallsved og pellets er lav, og anbefalles derfor til bruk i fjernvarmeanlegg for å redusere de totale klimapåvirkningene fra slike systemer. Pelletsproduksjon anbefalles som forbehandlignsmetode i Norge på grunn av lave klimaeffekter fra forbehandling.

Den norske regjeringen har ambisiøse mål om å redusere drivhusgassutslippene betraktelig mot 2020, og har mål om å være klimanøytrale innen 2030. Referansescenarioet evaluert i denne oppgaven viser et globalt oppvarmningpotensiale på 134 gram CO_2-ekvivalenter per kWh, mens det alternative scenarioet viser en klimaeffet på 136 gram CO_2-ekvivalenter per kWh. Basert på disse verdiene, drivhusgassutslippene kan reduseres mot 2020 ved hjelp av norsk bioenergiproduksjon, men på grunn av vesentlige klimaeffekter fra biogene CO_2-utslipp kan ikke bruk av bioenergi muliggjøre målet om å bli klimanøytrale innen 2030.

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ABBREVIATIONS

AP	acidification potential
BEF	biomass expansion factors
CHP	combined heat and power
C&D waste	construction and demolition waste
CW	clean wood
DH	district heating
FETP	freshwater ecotoxicity potential
FR	forest residues
GHG	greenhouse gases
GWP	global warming potential
LCA	life cycle assessment
LCI	life cycle inventories
LHV	lower heating value
MC	moisture content
PMFP	particulate matter formation potential
P&C waste	paper and cardboard waste
SR	saw residues
TOP	torrefied pellets
WW	waste wood

1 INTRODUCTION

The use of bioenergy in Norway is 17 TWh (SSB, 2011a) and the Government has put forth goals to increase both use and supply. There are substantial amounts of boreal forest in Norway, and the standing and growing forest today is 2,5 times greater than what was the case 80-90 years ago (Landbruks- og Regjeringen, 2011). Additionally, waste resources and by-products from industry contribute to a further availability of bio-resources. Bioenergy is the only carbon based renewable energy source we know today, and has the potential to replace fossil energy resources. In Norway, almost all energy use originates from renewable sources, and only 5 % of the total GHG emissions in Norway are caused by the energy sector (Regjeringen, 2007). Bioenergy accounts for 6 % of the Norwegian energy supply (Scarlat et al., 2011). The great amount of forest and waste resources available in Norway suggest that bioenergy can be pursued as a climate mitigation option. Globally, more than 80 % of the energy use will be based on fossil fuels as industrialisation takes place in developing countries (Metz et al., 2007), with consequently high GHG emissions. The role of renewable energy sources is therefore crucial.

The Norwegian government put forth in 2008 a strategy to increase the use of biomass by 14 TWh by 2020 (Regjeringen, 2011). This implies a doubling of bioenergy use compared to 2008. The strategy of increased use of bioenergy is further stressed in the recent white paper on climate efforts released by the Norwegian Government in April 2012 (Regjeringen, 2012). Subsidies are implemented for chipping of forest resources and construction of new bioenergy infrastructure units to reach this goal, and in addition, the B*ioenergy programme* is stimulating farmers to produce, use and deliver bioenergy. The role of bioenergy is also stressed by the European Union. Increased production and use of bioenergy has been a politically desirable option in Norway, and an expected growth in the bioenergy sector can play an important role for value added and employment

(Langerud et al., 2007). Forest resources have also, through several centuries, been crucial for the Norwegian economy (Vennesland et al., 2006).

Bioenergy is competitive in the Norwegian market, which is important for increased use (Energidepartementet, 2008). Both electricity and oil prices have increased in recent years, which is not the case for most bioenergy systems. Also, regulations impose public buildings above 500 m^2 to utilise waterborne heating distribution (Trømborg, 2011). The Norwegian Government seems to have prioritised the role of bioenergy in the Norwegian market. The same government has a target to become carbon neutral by the year 2030 and decrease the GHG emissions by 15-17 million tonnes of CO_2-equivalents by 2020. To meet the Norwegian Government's goal of increased use of bioenergy and at the same time decrease the GHG emissions, the climate change potential of Norwegian bioenergy is crucial. The sustainability of Norwegian bioenergy should therefore be assessed to ensure the expected climate benefits.

1.1 State of the art

Life cycle assessment is agreed to be the best option to measure the environmental impacts, and in particular measuring the global warming potential (GWP) from greenhouse gases for bioenergy based systems (Cherubini, 2010). This study will assess the life cycle impact from several biomass based systems producing energy. A set of feedstocks, pre-treatment options, energy conversion technologies, and distribution methods are analysed and compared in this thesis. The entire life cycle of a total of 80 bioenergy systems will be analysed. Following is a review on available literature investigating feedstocks, treatment technologies, energy technologies and distribution methods relevant for this thesis. Methodological aspects regarding inclusion of greenhouse gas emissions from biomass storage and treatment of biogenic CO_2 will also be examined.

Biomass for energy purposes is found to reduce GHG emissions by 55 % to 98 % compared to fossil sources (ECF et al., 2010), and many have investigated the increased use of bioenergy in Norway to the year 2020 (ECF et al., 2010; KanEnergi, 2007; Langerud et al., 2007). Norwegian bioenergy has been investigated by many (Scarlat et al., 2011; Trømborg et al., 2008; Trømborg et al., 2011; Trømborg and Solberg, 2010; Valente et al., 2011), with a particular focus on forestry and heating. Also the policy effects of Norwegian bioenergy originating from forests have been assessed (Sjølie et al., 2010; Trømborg et al., 2007), and it is found that investment support for new bioenergy heating units increase the consumption, but will not necessarily lower the GHG emissions. On the other hand, an increased carbon tax on competing fossil resources will have a positive effect on bioenergy production. Further, competitiveness and production levels are strongly dependent on the general energy price. Few central bioenergy heating units in Norway, together with low electricity prices is stated to be the reason for the low market share of bioenergy in Norway.

In this thesis, a total of six feedstocks are assessed; stemwood, forest residues, energy wood, sawmill residues, wood waste and paper and cardboard waste. Many have investigated forest resources (Eriksson and Gustavsson, 2008; Lindholm, 2010; Mitchell, 1992). Raymer (2006) compared six feedstocks for energy production in Hedmark, Norway using LCA, and found that demolition wood combusted in a district heating unit has the lowest environmental impact with an average GWP of 11 kilograms CO_2-equivalents per m^3 demolition wood. The GWP of sawdust combusted directly is found to be 25 kilograms CO_{2-}equivalents per m^3 sawdust, while the climate change potential from pellets made from saw residues combusted in a central heating unit was found to be just below 13 grams CO_{2-}equivalents per kWh. Methane and N_2O emissions are included for combustion emissions, but the wood resources are considered carbon neutral. Many have investigated the use of waste for energy (Eriksson et al., 2012; IEA-Bioenergy, 2005), and Jesawni et al. (2012) state that waste incineration for energy is advantageous over landfilling with biogas collection.

In this study, seven different biomass pre-treatments options will be assessed; chipping, pelletising, integrated torrefaction and pelletising, a direct saw residues case, saw residue pelletising, and integrated torrefaction and pelletising from saw residues. The saw residues cases are separated from the remaining treatment options as no chipping is required prior to further treatment. The seven treatment options result in four pre-treated *products*, i.e. chips, pellet, torrefied pellets and saw residues (from the direct saw residues case). These four pre-treated materials will be discussed now.

Chipping is widely used, and many have looked at chipping of forest resources in general (Gronalt and Rauch, 2007; Kärhä, 2011; Suadicano, 2003). There are numerous studies investigating the environmental impact from chips systems (Eriksson and Gustavsson, 2010; Eriksson and Gustavsson, 2008; Forsberg, 2000; Siegl et al., 2011; Wihersaari, 2004). Wihersaari (2004) found life cycle GHG emissions from forest residues collection from final harvest to combustion in a modern CHP unit of 6-9 grams CO_2 equivalents per kWh. Forsberg (2000) assessed several biomass based systems, of which two utilised the treatment option of chipping. The first case was a tree section case with a GWP of 26 grams CO2-equivalents per kWh electricity, while the second was a baled forest residue case with a GWP of 34 grams CO_2 equivalents per kWh. Korpilahti (1998) reported life cycle

CO_2 emissions between 10-14 kilograms per m^3 for use of Finnish forest residues, depending on what time in the value chain chipping takes place.

Forsberg (2000) assessed a third case; a pellet case with 32 grams CO_2 equivalents per kWh. There have been performed several LCAs of pellet systems (Fantozzi and Buratti, 2010; Hagberg et al., 2009; Sikkema et al., 2010; Sjølie and Solberg, 2011). Hagberg et al. (2009) assessed three options of raw material – roundwood, wet sawdust and dry saw shavings, and found a GWP in the range 10-14 grams CO_2-equivalents per kWh for Swedish conditions. Also Sikkema et al. (2010) investigated pellet production from saw residues, and found a GWP of about 11 grams CO_2-equivalents per kWh for large-scale pellet use in district heating, and a GWP between 36 and 70 grams CO_2-equivalents per kWh for large-scale power production in the Netherlands. Sjølie and Solberg (2011) assessed the GHG emissions from Norwegian wood pellet, and found life cycle GWP between 24 and 482 kg CO_2-equivalents per kWh, where the lower end of the GWP is for raw materials supplied locally. Canadian import was considered in this study, and pellet import from Canada to Europe has been considered by others too (Magelli et al., 2009; Pa et al., 2012).

Torrefaction leads to favourable biomass properties, and the technology is foreseen to have a huge market potential (Kleinschmidt, n.d.). Torrefied biomass can be utilised in large-scale power production, in district and residential heating as well as industrial energy production. The technology is currently entering the commercial demonstration phase in Europe, and the technology in general is well documented (Arias et al., 2008; Chen and Kuo, 2010; Chen and Kuo, 2011; Li et al., 2012b; Repellin et al., 2010; Stelt et al., 2011). Sawdust and forest wood are feedstocks often analysed. Many have investigated the potential of torrefaction as a thermal pre-treatment option for energy generation (Bergman et al., 2005; IEA-Bioenergy, 2010a; Pentananunt et al., 1990; Prins et al., 2006; Tumuluru et al., 2011), where the integrated torrefaction and pelletising (TOP) process has been a focus (Bergman, 2005; Li et al., 2012a; Uslu et al., 2008).

Looking at energy conversion technologies, many have investigated emissions from wood combustion in fluidised bed boilers (Broek et al., 1996; Leckner and Karlsson, 1993; Nussbaumer, 2003), and others discuss energy production from biomass in general (IEA-Bioenergy, 2010b; McKendry, 2002). In this thesis, five conversion options will be assessed; CHP plants with electricity and heat demand, a district heating plant, a thermal power plant producing electricity, and a steam-producing boiler. Eriksson et al. (2007) is comparing waste and biomass incineration in a district heating and CHP plant, and find that waste incineration and the CHP option have the largest GWP savings. Gustavsson (1997) is comparing heat and electricity production from biomass, and states that less efficient systems lead to greater CO_2 emissions and higher primary energy use. The relationship between CO_2 emissions and efficiency is stated to not apply for systems assuming carbon neutrality. Generally, Cherubini and Strømman (2011) state that the GHG emissions from one unit of electricity produced from biomass is only 5-10 % of that of fossil based electricity production. The ideal conversion route is in a CHP plant.

Several LCA studies have been performed on combined heat and power plants fuelled by biomass, where some of these will be discussed here. Guest et al. (2011) performed a life cycle assessment comparing micro, small and medium scale CHP gasification. The CHP plants were fuelled by a mix of forest and sawmill residues, and transport distances for the different alternatives ranged from 15 – 108 km. The general result of the study showed that the small-scale CHP option was a better environmental choice in five out of the ten impact categories analysed, and it never ranked worse. Also Jugmeier et al. (1998) and Casirini et al. (2010) analysed the life cycle impacts from biomass based CHP systems.

In addition to life cycle assessments looking at CHP plants, there are several studies investigating the environmental burden associated with electricity production from short rotation coppice (Goglio and Owende, 2009; Lettens et al., 2003; Styles and Jones, 2007). Further, some have looked at electricity production from short rotation coppice using the technology of integrated gasification combined cycle (IGCC), without carbon capture and storage, CCS (Rafaschieri et al., 1999) and integrated with CCS (Corti and Lombardi, 2004; Klein et al., 2011). There are also performed several LCA’s looking at biofuels co-combusted with coal (Hartmann and Kaltschmidt, 1999; Heller et al., 2004).

The environmental burdens of steam producing systems from biomass have not been subject to the same investigation as has been the case for electricity and heat production from biomass resources. Some studies have performed life cycle assessments of steam production (Cetinkaya et al., 2012; Gonzáletz-Garcia et al., 2011; Liu et al., 2011) – assessing resource use of lignite, dried sludge, used oil, bio-refinery waste, biogas and methanol. Investigating energy distribution, LCAs have been performed for district heating distribution systems (Fröling et al., 2004; Fröling and Svanström, 2005; Persson et al., 2006). Also the environmental impacts of power distribution are assessed (Bumbky et al., 2010; Jorge et al., 2012; Jorge et al., 2012; Weber et al., 2010). Main findings for heat and electricity distribution showed that losses during transmission and distribution accounted for the bulk of the climate change impacts, where construction also is of high importance for heat distribution.

To date, life cycle analyses investigating biomass systems have assumed that carbon released from biogenic sources, i.e. carbon in biomass, is climate neutral (Cherubini and Strømman, 2011). Both the IPCC and EU RED consider bioenergy as carbon neutral (Sjølie and Solberg, 2011), while Cherubini et al. (2011b) states that CO_2 released from biomass does have a climate effect before it is being sequestered. Guinée and Heijungs (2009) compare LCA results for different methods of handling of both biogenic CO_2 and allocation issues, and states that both are of high importance for the methodology of LCA.

Cherubini (2010) states that the three greenhouse gases CO_2, CH_4 (methane) and N_2O (nitrous oxide) should be accounted for in all stages of the life cycle for a bioenergy system investigating the global warming potential. These stressors are important with regards to fertiliser use and organic decomposition, where only the latter is of importance for this assessment. Emissions of N_2O are often not included, and if they are, they are mostly default emission factors from IPCC; but these factors were found to underestimate the N_2O emissions in the range of three to five times (Cherubini et al., 2009). Also Cherubini and Strømman (2011) state that N_2O emissions from organic matter decomposition in soil is an important variable in LCA studies.

1.2 Objective

This study will assess the environmental performance of Norwegian bioenergy. The methodology of life cycle assessment will be used to evaluate environmental impacts, and life cycle inventories are produced for a set of feedstocks, treatment options, energy conversion choices and distribution methods. Two transport steps are also included. The inventories are put together to present 80 value chains for Norwegian bioenergy conditions. Differences in environmental impacts for the different value chain steps will become evident for the four impact categories assessed. The global warming potential impact category will be the most important. Finally, two scenarios are assessed; one for the current Norwegian system and an alternative scenario for the year 2020. The climate change impact potential of these scenarios is investigated and recommendations for Norwegian bioenergy will be presented.

It is important to model the greenhouse gas emissions as accurate as possible when assessing the global warming potential from bioenergy systems. Both biogenic CO_2 emissions from the biomass systems and GHG emissions from biomass storage and decay are included. In addition to CO_2 emissions, N_2O and CH_4 emissions will be accounted for chips storage, according to Wihersaari (2005). This will increase the environmental consequences from storage and decay. Biogenic carbon dioxide emissions are included according to Cherubini et al. (2011b) with the use of biogenic global warming potential factors, GWP_{bio} factors. A factor is assigned to CO_2 emissions throughout the value chains, accounting for its climate change impact potential. The use of GWP_{bio} factors is expected to influence the climate effect from the biomass based energy systems significantly. Surface albedo effects are also included in the assessment of GWP, and will contribute to a negative global warming potential for several of the assessed forest resources. Biogenic CO_2 emissions, surface albedo effects and GHG emissions from storage are all discussed in more detail at the end of the methodology chapter.

1.3 Content

The study is structured in the following manner; the methodology of life cycle assessment is first introduced in chapter two, including the mathematical framework for LCA and treatment of biogenic CO_2 emissions, surface albedo effects and emissions from biomass storage. Several materials and technologies are investigated in this thesis, and theory for these will be presented in chapter three. The modelled system is then described in detail in chapter four and chapter five. The process LCA case descriptions in chapter four will present flowcharts, and discuss inventories and assumptions made for the Norwegian bioenergy systems. Chapter five presents and discusses the scenario model. The reference scenario, presenting the current Norwegian bioenergy system, is explained together with a development of the alternative scenario. The results for both the unit based process LCAs and the scenarios are then presented in chapter six. Finally, in chapter seven there will be a discussion of the results. Recommendations for Norweian bioenergy developments are presented together with a discussion of the key assumtions in the model as well as benchmarking of the results. A conclusion of the main findings will be presented in the end.

2 METHODOLOGY

This chapter will introduce the methodology used in this study; Life Cycle Assessment (LCA). Basic mathematics of LCA, allocation issues, and the applied life cycle impact assessment method, ReCiPe, will all be introduced. In addition, the impact category of climate change is highly relevant for this study, and both handling of biogenic CO_2 and forest surface albedo effects will be discussed. The chapter ends with a discussion of storage of biomass and related losses and emissions.

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool for identifying and evaluating the environmental aspects of products and services from “the cradle to the grave” (…)”(ISO Central Secretariat, 2009, p. 6). An LCA includes processes which analyse the whole life cycle of a product or service, including everything from the extraction of the resource, final utilisation, disposal, and waste management of the given resources in the system. Inputs to the life cycle chain are energy and raw materials, and the outputs are useful products, both final products and by-products, as well as emissions to air, soil and water (Cherubini, 2010). In this way, the overall environmental performance of a system can be evaluated, and this is particularly interesting in a decision making perspective.

LCA can be used as a decision making tool, and when applied as such it is important that the system boundaries are consistent and that no double counting takes place. Therefore the LCA framework is standardised through the ISO 14040 standards. These standards present guidelines on how to conduct and perform an LCA, and offer a way to perform LCAs that are not based on inconsistent system boundaries which might favour one system over the other on false premises (ISO Central Secretariat, 2009).

An LCA which is in accordance with the ISO standards is composed of four different step, see Figure 1. The first step is the goal and scope definition, and this phase defines the context of the analysis and formulates the problem (Brattebø et al., 2007). The system definition includes the scale of the system boundaries, setting out the main lines of the study, where the system boundaries specify which unit processes are part of the total system (ISO, 2006). In the next step, the inventory analysis, the bulk of the modelling takes place (Brattebø et al., 2007). This is the most technical part of an LCA study, and the result of this phase is the life cycle inventory (LCI) model. The inventory is further used in the impact assessment step, where final impact of the system can be determined. Impact categories and characterisation factors are used together with the inventory tables to generate the impacts associated with the final demand - see mathematical framework below for more information. Finally, the last step is the interpretation step. This phase makes room for discussion and analysis of the results in connection to all earlier steps, and is a continuous process in life cycle assessment. In addition, sensitivity analysis can be performed related to the life cycle impact assessment (LCIA), and is meant to estimate the effect of choices made in the assessment (ISO, 2006).

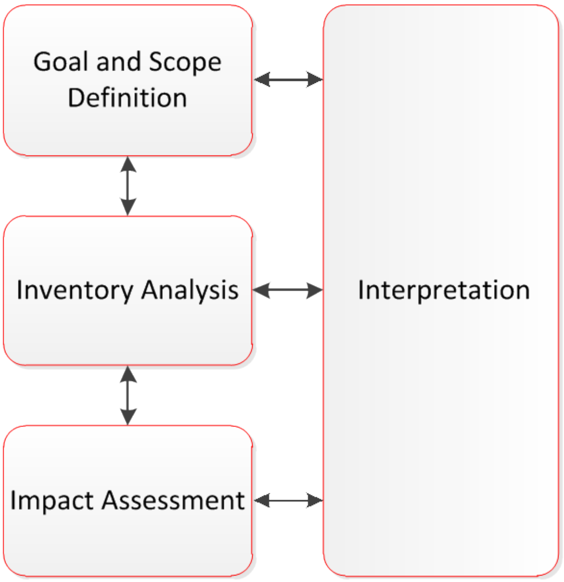

Figure 1: the four phases of LCA (ISO, 2006)

LCA generally distinguishes between foreground and background systems. The background system is based on generic data from databases, like Ecoinvent which is used in this study, and the data in the foreground system is generally specific for the study in question (Strømman, 2010). The background and foreground systems describe the interdependency between different processes in a study, and together, the systems make up a requirements matrix, A, see equation 1.

$$A = \begin{bmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{bmatrix} \tag{1}$$

The coefficients in the requirement matrix, a_{ij}, represent the amount of process *i* required per output of process j, and the sub-systems A_{ff} and A_{bb} show the requirements between the different foreground processes and background processes respectively (Strømman, 2010). The A_{bf} matrix describes the input processes from the background system to the foreground system.

The A matrix can be used to generate the activity in each process related to the final functional unit by setting the production in a process equal to the demand in the same process (Strømman, 2010). The demand is put together of intermediate and external demand, where the intermediate demand is the internal demand in the system, and is equal to the requirement matrix times the production. The final demand is the final product delivered by the system to the market, which is generally described as the functional unit. In this assessment, the functional unit is 1 kWh electricity delivered from the system investigated. Equation 2 presents the production-demand relationship in matrix form.

$$x = Ax + y \tag{2}$$

Equation 3 is the solution to equation 2, solved for the unknown output vector, x. The L matrix is called the Leontief inverse, and is the *cooking recipe* with coefficients representing the amount of output of process *i* that is required per unit final delivery of process j (Strømman, 2010). This means that the Leontief Inverse matrix is per unit external demand of the process in each column.

$$\begin{gathered} x = Ax + y \Leftrightarrow (I - A)x = y \Leftrightarrow x = (I - A)^{-1}y \\ x = Ly \end{gathered} \tag{3}$$

$$where, L = (I - A)^{-1}$$

To find the overall emissions, the x vector is used together with the stressor intensity matrix, S, see equation 4. The stressor matrix, S, contains the stressors and S_{ij} gives the stressor per unit output of process j. The vector e in equation 4 then gives the stressors associated with the final demand.

$$e = Sx \tag{4}$$

Finally, total impacts from the system can be found using equation 5, characterising all stressors to the different impact categories (more below). Each stressor can contribute to several impact categories, and the factors in the characterisation matrix convert these stressors to equivalents of impacts – all per unit external demand.

$$d = Ce \tag{5}$$

where, C: characterisation matrix

Equation 6 and 7 give the contribution of each process or stressor respectively to the different impact categories. Both these equations are important in order to understand the total impact from a system, as a process' or stressor's contribution to the overall impact is determined. The row sum of both equation 6 and 7 give the total impact vector, d, see equation 8.

$$D_{pro} = CS\hat{x} \tag{6}$$

$$D_{str} = C\hat{e} \tag{7}$$

$$d = \sum_{pro} D_{pro} = \sum_{str} D_{str} \tag{8}$$

For systems generating more than one final product, i.e. producing by-products in addition to the functional unit, allocation of the total impact is important. For bioenergy systems producing several outputs, like electricity and heat from a CHP plant, allocation will be essential (Cherubini, 2010). There are several ways to deal with multiple outputs, and the partitioning approach is introduced below as this is the method used in this assessment (Strømman, 2010).

The partitioning approach assigns a share of the total impacts to the different products, based on properties like energy, economy and exergy (Strømman, 2010). The choice of allocation property will have a great impact on the results - and should therefore be carefully investigated (Cherubini, 2010). Looking at combined heat and power, equation 9 shows the basic principle, where the final demand is put together of the two products electricity and heat.

$$d_{CHP} = CSLy_{CHP} = CSL(y_{el} + y_{heat}) = d_{el} + d_{heat} \tag{9}$$

The share of impacts assigned to electricity and heat is between zero and one, and the distribution of impacts between electricity and heat is as shown in equation 10.

$$d_{el} = \alpha d_{CHP} \tag{10}$$

$$d_{heat} = (1 - \alpha) d_{CHP}$$

The method used for the life cycle impact assessment, i.e. the characterisation method, is ReCiPe 2008, which provides a way to calculate life cycle impact category indicators (Goedkoop et al., 2009). Three different perspectives are available for use; individualist (I); hierarchist (H) and egalitarian (E). Respectively, the first is based on short-term interest and technology optimism, the second is somewhere in between the others and represents common policy principles, and finally, the last perspective is the most precautionary of them all and the one most concerned with sustainability. The three approaches each have different use of time horizons; the individualistic perspective uses a time horizon less than 100 years. In this assessment, the hierarchist (H) perspective will be used, which has time horizons of 100 years for climate change and terrestrial acidification, 100 000 years for ionising radiation, and infinite time horizon for human toxicity and for the ecotoxicity categories.

This study will use midpoint indicators. The midpoint indicators are linked to life cycle impact categories as shown in Figure 2. The midpoint indicators are further linked to the endpoint indicators, given on the right in Figure 2. Looking into climate change, the related midpoint indicator is infrared forcing, expressed as kg CO_2-equivalents. The related impact category indicator at endpoint level is put together of two indicators: damage to human health and terrestrial damage. This example points to the fact that the environmental mechanisms are twofold, given on both a midpoint and endpoint level, where only the midpoint level is assessed in this study.

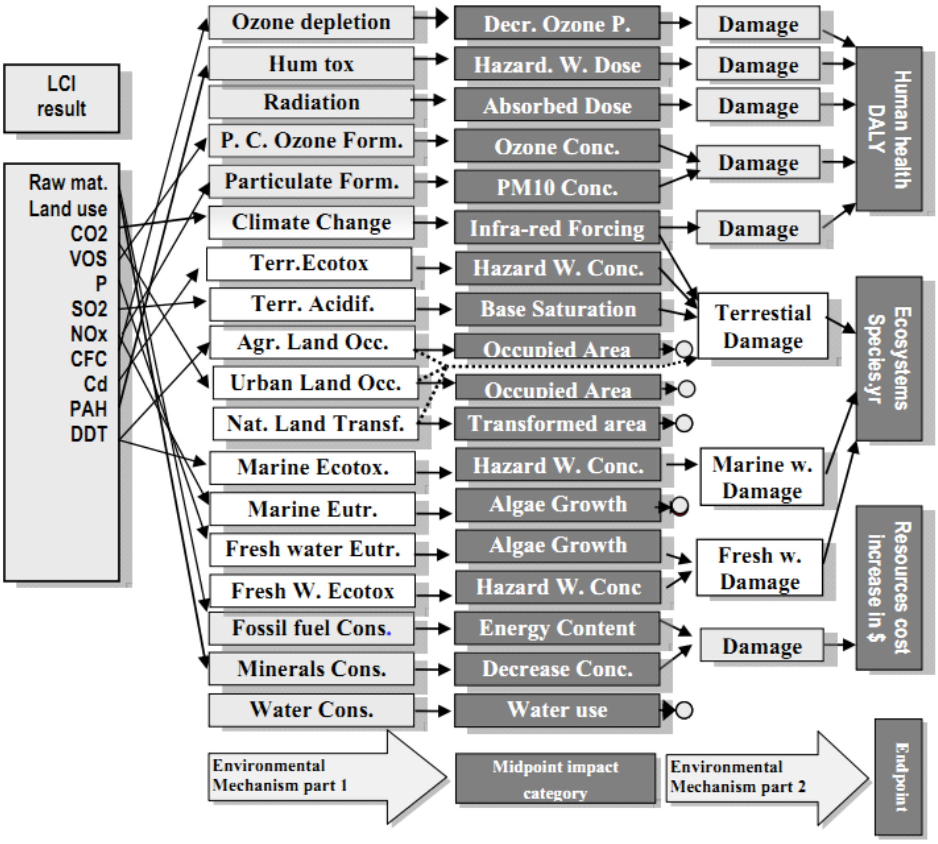

Figure 2: relationship between impacts categories, midpoint indicators and endpoint indicators (Goedkoop et al., 2009).

There are several impact categories available, many shown in Figure 2. Different impact categories are of importance for different studies. For the bioenergy systems assessed in this thesis, the life cycle impact categories presented in Table 1 are considered to have the highest degree of importance. A total of 18 impact categories are given in Figure 2, where only four are presented in Table 1. Climate change potential, or global warming potential, is the impact category which is most important for this study. The impact of GHG is global and contributes to climate change. The remaining three impact categories all have regional impacts. Particulate emissions are important for biomass combustion, and are included in the particulate matter formation category. Terrestrial acidification and freshwater ecotoxicity contribute to acidification of terrestrial environment and toxicity of aquatic environment respectively.

Impact Category		
Name		***Unit***
Climate change	*GWP*	kg CO_2-eq
Terrestrial acidification	*AP*	kg SO_2-eq
Particulate matter formation	*PMFP*	kg PM_{10}-eq
Freshwater ecotoxicity	*FETP*	kg 1,4-DCB-eq

Table 1: ReCiPe 2008 (H) impact categories relevant for this thesis.

2.2 Biogenic CO_2

Traditionally, CO_2 released from biomass combustion systems is thought to be climate neutral: the CO_2 released from combustion is approximately equal to the carbon sequestered in biomass (Cherubini et al., 2011b). Carbon has been treated as a temporary loss that has no net impact. Cherubini et al. (2011b) states that CO_2 from biomass combustion in fact will contribute to global warming before an equivalent amount of CO_2 gets sequestered, i.e. while the CO_2 is still in the atmosphere it has a climate effect. Figure 3 shows this; biomass standing in forest is at steady state (a), and as the biomass is harvested, all aboveground carbon is emitted to the atmosphere (b). The time frame between (b) and (c) represents the rotation period, and throughout the rotation, carbon is sequestered, before all carbon is sequestered at the end of the rotation period.

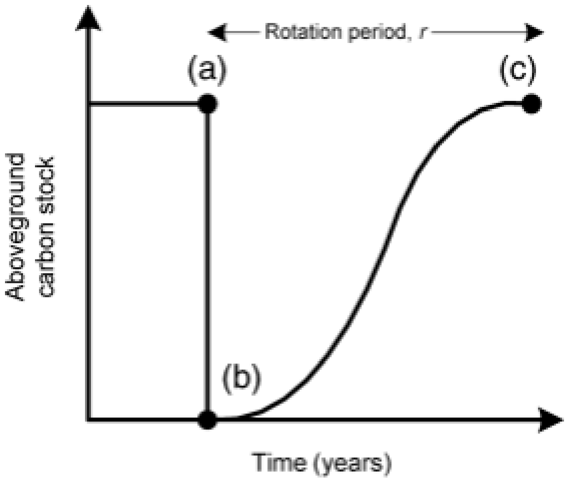

Figure 3: simplified picture of a carbon neutral system (Cherubini et al., 2011b).

For a forest system that will regrow in 100 years, the biomass combustion system will be carbon neutral at the end of these 100 years, but not before (Cherubini et al., 2011b). This is changing the way CO_2 emissions are being treated from biomass combustion systems, and the treatment of biogenic CO_2 emissions in this analysis will follow the principles of Cherubini et al. (2011b). Factors representing the biogenic CO_2 impacts to fossil CO_2 impacts are presented below for all feedstocks assessed in this thesis.

As mentioned earlier, in LCA three time horizons are normally applied; 20 years, 100 years or 500 years. A time horizon of 100 years is used in this analysis in combination with the full impulse response function (IRF): CO_2 in the atmosphere can be absorbed by both the oceans and the terrestrial biosphere. There are two other models available; the vegetation IRF, which only includes uptake of CO_2 from biomass regrowth, and the ocean and vegetation IRF, which also includes uptake of CO_2 from oceans. Shorter rotation biomass, like roadside thinning wood, will have a smaller climate impact, as the CO_2 released to the atmosphere has less time to cause an impact before an equivalent amount is being sequestered.

To calculate the cumulative climate impact from a biomass based combustion system, global warming potential indexes are used, GWP_{bio} (Cherubini et al., 2011b). This factor is between zero and one, and should be multiplied by the direct, biogenic CO_2 emissions from the biomass system in question to get the relative contribution to global warming. The index is relative to the global warming potential of anthropogenic, fossil CO_2 emissions, and is dependent upon time horizon and rotation period. The rotation period used throughout this assessment for final stemwood and forest residues harvest is 100 years. This is based on the fact that boreal forest has a regrowth period between 80 and 100 years. A time horizon of 100 years is assumed, being the most common time frame used in practice (Forster et al., 2007). Also saw residues are assumed to have the same GWP_{bio} factor as stemwood and forest residues. The rotation period for thinning wood is assumed to be 20 years. Table 2 shows the GWP_{bio} indexes used for stemwood, forest residues, energy wood and saw residues. Generally, the GWP_{bio} factor is increasing with increasing rotation period and decreasing with increasing time horizon.

	GWP_{bio} factor
Stemwood	0.43
Forest residues	0.43
Energy wood	0.11
Saw residues	0.43
Wood waste	0.25
P&C waste	0.39

Table 2: GWP_{bio} factors assigned to different feedstock options.

The GWP_{bio} factors for waste resources differ from the factors discussed for forest resources, as waste resources have been in the anthroposphere for some time before becoming waste. While in use, the carbon in the materials is stored, and the climate impact from this carbon is delayed (Cherubini et al., 2011c). Probability distributions are applied to obtain GWP_{bio} factors including the time-distributed CO_2-fluxes. To find the correct factors, the product lifetimes of the waste resources are important, as these are included in the calculation of the GWP_{bio} factors. Wood products typically have a long lifetime in the anthroposhere, while packaging have a shorter lifetime (Frøyen and Skullerud, 2000). Frøyen and Skullerud report both an upper and lower limit for different waste product lifetimes, and the upper limits are used in this thesis. Wood wastes have an assumed lifetime of 20 years, while paper and cardboard waste have an assumed lifetime of two years. Saw residues are not considered a waste resource, but rather a by-product from the wood processing industry. The GWP_{bio} indexes for wood waste and P&C waste are found using the product lifetime together with a forest wood rotation period of 100 years, giving the factors presented in Table 2.

2.3 Surface albedo effects

Surface albedo is defined as *the ratio of reflected radiation from the surface to incident radiation upon it* (Bright et al., 2012, p. 4). The ratio is between zero and one, where a ratio of zero represents a black body and a ratio of one is for a white body. In LCA, albedo effects are significant for the global warming potential. For extraction of boreal forest, which is modelled in this study, the albedo will change at the point of harvest. At some point, the albedo will become the same again, but before this time, radiative forcing will occur – implying an albedo impact. The albedo for boreal forest is low compared to surrounding land, particularly when snow is present. This means that boreal forest extraction will increase the local albedo, reflecting more incoming solar radiation, which is beneficial for the global climate. The GWP of albedo change is both region and case specific.

Mean annual albedo for clear-cut harvest of stemwood is 0,27, while the mean annual albedo for integrated stemwood and forest residues harvest is 0,30 (Bright, pers.com.). Two forest resource extraction cases are considered in this thesis: energy wood harvest and integrated stemwood/forest residues harvest. Removing forest residues in addition to stemwood changes the albedo, implying a slightly higher clear-cut albedo. Overall, the surface albedo effects are greatest for integrated stemwood and forest residues harvest, as the mean annual albedo for clear-cut harvest is higher than what is the case for separate stemwood harvest. In this thesis, albedo effects for neither energy wood nor waste resources are considered. The stemwood harvest case considered in this thesis is modelled as integrated with forest residues harvest, and the albedo effects for stemwood and forest residues are therefore modelled the same. Also the saw residues cases considered will have the same albedo effect as stemwood and forest residues, as sawmill wood arise from the same resource as stemwood. The GWP_{100} of albedo change is used to asssess the overall surface albedo effects. For Hedmark county in Norway, a value of -4127 grams CO_2-equivalents per m^2 clear-cut is used. For a maximum sustainable removal, a yield of 56 tonnes carbon per hectare is utilised. Combining these values give an overall surface albedo of -0,74 grams CO_2-equivalents per gram carbon. Normalizing to CO_2, a value of -0,20 grams CO_2-equivalents per gram CO_2 is found. This factor is then multiplied by the total GWP of the assessed systems and added to the same total. This will decrease the GWP of the forest resource systems, pointing to the surface albedo benefit from forest extraction.

2.4 Storage losses

Biomass storage is an important focus of this assessment and storage issues are discussed in this part. Biomass can be stored in many different forms, e.g. as raw, untreated biomass, chips, pellets or torrefied pellets. Storage might imply losses, referred to as dry-matter losses. Decomposition is the process where a change in proportions of cellulose and lignin contents occurs (Thörnqvist, 1985). Both storage of *non-comminuted* biomass and *comminuted* biomass are discussed here, starting with non-comminuted biomass storage.

For biomass storage, dry-matter losses generally present carbon losses. For non-comminuted biomass storage, carbon losses will result in carbon dioxide emissions, as the mass losses from storage will decompose. Equation 11 shows how the carbon dioxide emissions are calculated for non-comminuted biomass in this assessment. The calculation depends on several factors. The carbon content in biomass is multiplied by the losses, which gives the total carbon losses. A carbon content of 51 wt.% is used throughout this assessment (Loo and Koppejan, 2007; Skrifvars et al., 1997). This value would vary slightly throughout the value chain, but it is assumed that the carbon content remains constant, and also that the carbon content is the same for all feedstocks and pre-treated materials assessed. The carbon losses are further multiplied by the molecular weight of CO_2 over the molecular weight of carbon, resulting in the carbon dioxide emissions caused by the lost carbon. Equation 11 shows that the carbon dioxide emissions further are multiplied by both the GWP_{bio} factor and a factor of 0.99. The last factor points to the fact that 99 % of the carbon lost during storage is assumed to be emitted in the form of CO_2. The GWP_{bio} factor is discussed in page 17.

$$CO_2\ emissions_{non-comminuted\ storage} = \frac{cc}{100} * \frac{l}{100} * \frac{44}{12} * 0.99 * GWP_{bio}$$

where, cc: carbon content [%] (11)
l : losses [%]

Calculating the CO_2 emissions from storage of comminuted material takes a slightly different form, see equation 12. Unlike the CO_2 emissions from non-comminuted storage, a factor *f* is included; chips storage result in both nitrogen dioxide and methane emissions (see below) in addition to the carbon dioxide emissions (Wihersaari, 2005). *f* represents the share of carbon going to CO_2 emissions, and *(1-f)* is then the amount of carbon going to methane emissions. The moisture content is included so that the CO_2 emissions are calculated on a dry basis.

$$CO_2\ emissions_{chips\ storage} = \frac{cc}{100} * \frac{l}{100} * (1 - MC) * f * 0.99 * GWP_{bio}$$

f: share of carbon emitted as CO_2 (12)
MC: moisture content []

Both methane and nitrogen dioxide emissions are calculated based on emission factors from Wihersaari (2005). Emission factors are given on a per-day basis:

- $60\ \frac{\mathrm{g\ CH_4}\,emissions}{\mathrm{m^2 * day}}$
- $1.2\ \frac{\mathrm{g\ N_2O\ emissions}}{\mathrm{m^2 * day}}$

To have these values on a per kilogram basis, the height of the storage pile (together with the density) is the decisive parameter. A height of 10 metres is assumed. This might be slightly high compared to literature indicating pile heights of 2.5 to 7 meters (Eriksson, 2011; Gislerud, 1990; Hakkila, 2003; Jirjis, 1995). All pre-treatment options assessed in this study are assumed to take place at a separate treatment facility or energy conversion site, and it is therefore assumed that the chips pile heights will be higher than piles stored in forest or at landing.

Storage of untreated material and storage of comminuted material are discussed above, and in addition to chips, more pre-treated materials are assessed in this thesis.

Storage of both pellets and torrefied pellets (TOP) have an efficiency of one (Forsberg, 1999), i.e. there are no dry-matter losses. Therefore, no emissions will occur either. Dry-matter losses from saw residue storage are treated like comminuted biomass storage, i.e. calculated from equation 12. N_2O and methane emissions from saw residues storage are also calculated the same way as for chips storage.

3 THEORY

Feedstock, pre-treatment, energy conversion and energy distribution make up the assessed system in this study, and this chapter introduces and presents theory for these parts of the system. Several materials and technologies are assessed in this thesis, and theory for these is presented below.

3.1 Feedstock

A list of six feedstocks is assessed: stemwood, energy wood, forest residues, saw residues, paper and cardboard (P&C) waste and wood waste. The first three originate directly from forest and will be introduced first together with a discussion of Norwegian forestry in general.

More than one third of the Norwegian land area is covered by forests, and forestry has long traditions in Norway (Rognstad and Steinset, 2010). In the early 2th century worries regarding forest depletion arose, but the situation today shows that the forests have grown by 155 % compared to the first forest estimate 80 years ago. Forestry has a long time perspective as the time horizon from planting to final harvest is 60-120 years, and sustainable harvest therefore requires a long time horizon for planning (Langerud et al., 2007). Figure 4 shows the forest harvest in Norway in 2010 by county, the bulk of the Norwegian harvest taking place in the eastern parts of Norway (SSB, 2012a).

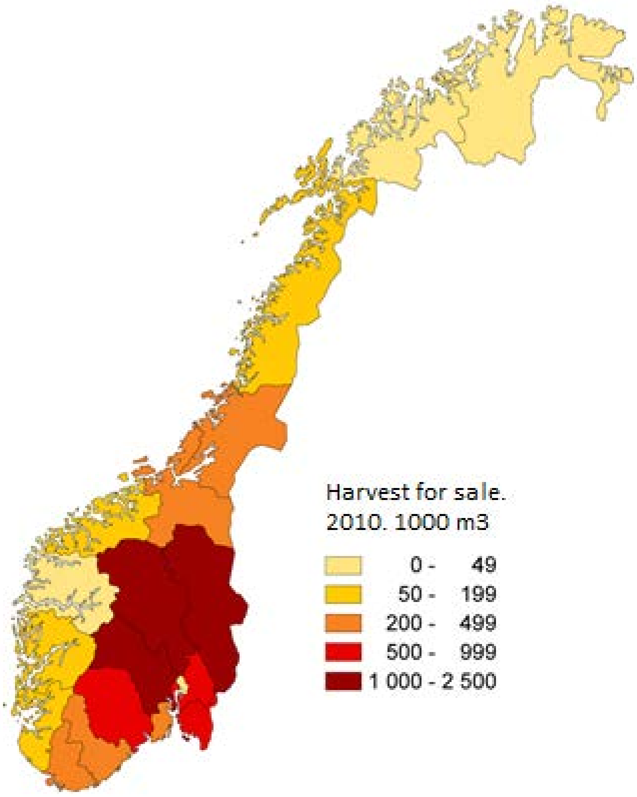

Figure 4: forest harvest by county in 2010 [1000 m^3] (SSB, 2012a).

Norway spruce (picea abies) is the most common wood species in Norwegian forests and makes up 50.5 % of the standing volume in the eastern parts of Norway (Yrjölä, 2001). Table 3 presents the fraction of tree species in forests in eastern parts of Norway, and shows that Scots pine (pinus sylvestris) and deciduous accounts for 36.5 % and 13 % respectively of the total volume. Spruce and pine make up the softwood tree species, while deciduous is classified as hardwood. Deciduous is assumed to consist of birch (betula pubescens) in this assessment. In the latter years, the share of deciduous trees in Norwegian forests has increased, while the share of pine has been constant (Rognstad and Steinset, 2010). The share of spruce has therefore decreased, and the reason for this pattern is a higher demand for spruce by industries. About three quarters of the tree harvested for sale is spruce, and about one quarter is pine. Deciduous only makes up about 1 % of the sold timber, as industries rarely use deciduous. Part of deciduous wood (e.g. for use as log) is not mapped, and therefore not covered by the numbers presented. In this study, a focus on species share *standing in forest* rather than species share sold to market has been chosen for the forest resources, as increased harvest for energy purposes is thought to be better represented by species standing in forest. An increased use of pine and deciduous is seen as one of the solutions for increased harvest levels (Vennesland et al., 2006).

Fraction of tree species	
Norway spruce	50.5 %
Scots pine	36.5 %
Deciduous	13.0 %
Softwood	87.0 %
Hardwood	13.0 %

Table 3: tree species fraction in eastern parts of Norway (Yrjölä, 2001).

Today, forest harvest mainly focuses on the stem of the tree, and roundwood is the largest component from forestry (SSB, 2012a). Roundwood has a dual use, both as input to pulp and paper manufacturing as well as for energy purposes (ECF et al., 2010). The use of roundwood for energy purposes is varying and dependent on the pulp and paper industry. In this study, roundwood harvest is referred to as final, stemwood harvest.

In addition to roundwood, both thinning wood and forest residues are produced from forest harvest. Unlike roundwood, these harvests are mainly used for energy purposes (ECF et al., 2010). In the eastern parts of Norway, 42 % of the forest land is in the age class beyond 81 years, while 58 % of the forest land is dominated by stand younger than 80 years (Yrjölä, 2001). Though almost 90 % of produced forest volume comes from final felling in Norway, producing forest biomass for energy purposes, thinning is an often used method of felling (Suadicano, 2003). Roundwood supply focuses on the stem of the tree, while in a bioenergy perspective the whole tree can be utilised for energy purposes. Thinning wood is harvest of young-aged trees where the whole tree is used for energy – thinning wood is therefore also referred to as energy wood. Thinning harvest is positive for both biodiversity and recreation as the forest is opened for more light and the harvest method is more gentle than clear-cutting (Vennesland et al., 2006). In addition, thinning will contribute to the ambition of increased harvest levels as the forest has become substantially denser today compared to the last 80 years. Thinning harvest, and in particular forest residue harvest (see below), is less economically sensible, pre-dominantly because of economy of scale.

Forest residues are a by-product of wood harvest, both from thinning wood and final harvest (Alakangas, 2005), where the by-product from final, stemwood harvest is the focus of this assessment and also the pre-dominant case. Forest residues consist of a combination of branches, needles, tops and refused wood. Sweden has been utilising forest residues for several years, both in smaller and bigger, industrial combustion units (Sjølli, 2006), where the latter is the focus of this assessment. To ensure biodiversity and forest regrowth, the forest residue harvest should not be too intensive

(Langerud et al., 2007). Leaving the forest residues in piles in forest to dry can solve the problem of forest regrowth; needles and leaf will fall off and there will as well be some losses of branches and bark. This will obviously reduce the recovery rate, but nutrient is left in the forest for absorption by growing trees. In Finland, a rule of thumb is that about 30 % of the residues should be left on the forest floor.

Forests have a high degree of importance in Norwegian industry, and the sawmill and woodwork industries purchase yearly about half of the logged wood (Rognstad and Steinset, 2010). The pulp and paper industries purchase yearly about one third of the forest harvest for sale, while a small share is sold to particle- and fibreboard production. Normally about 10 % is sold to other Norwegian and foreign buyers. Overall there are several by-products from the wood processing industry: bark, cellulose chips, lumber/woodwork and sawmill residues (Langerud et al., 2007), where the latter is the only assessed by-product in this study. Saw residues are either utilised by the industry itself, producing thermal power for internal use, or used in particle board production or pellet production. Because of increased pellet production, this raw material has experienced increased competition, and therefore also increased prices.

Wood has been historically important in Norway, and wood waste is today an important material flow in the Norwegian market; compared to 1995, the amount of waste has increased by 30 % (SSB, 2012b). Figure 5 presents this increase together with waste treatment options. About one third of the waste is recovered, while about 20 % goes to energy production. Today there are 20 energy units combusting waste in Norway, and the amount of waste going to combustion for energy has doubled the last ten years. The remaining waste is used as filler or masking compound, combusted without energy recovery, or goes to landfill.

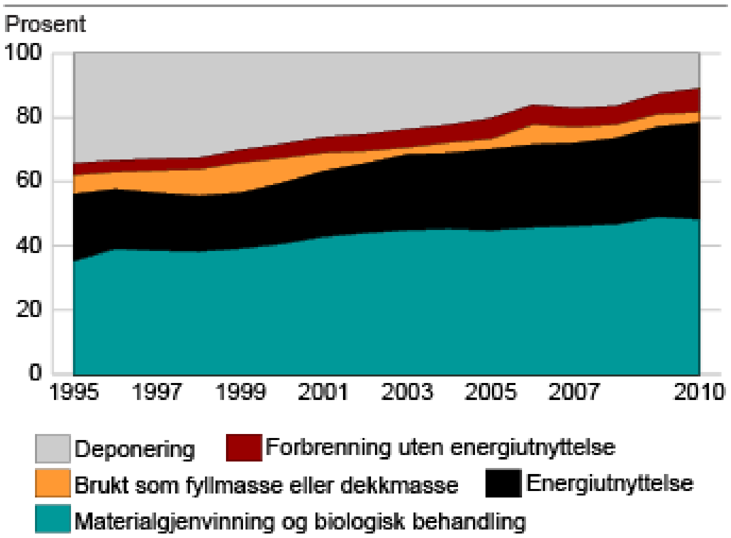

Figure 5: amount of regular waste in Norway from 1995 to 2010, divided by treatment (SSB, 2012b). Contaminated waste is not included.

Paper and cardboard (P&C) waste and wood waste are the assessed waste flows in this study. Compared to the total waste amount in Norway in 2010, P&C waste accounts for about 12 % and waste wood about 18 %. Paper and cardboard is sorted to a higher degree every year in Norwegian households, also in the cities, and this waste flow is therefore important (Langerud et al., 2007). Waste wood arises from all products containing wood, and C&D wood waste is considered to be an important contributor to the wood waste flow. Since wood products normally have a long life time, wood products introduced to the market today will normally become waste in 20 to 50 years from now (Frøyen and Skullerud, 2000), whereas stated above, the product lifetime upper limit is 20 years.

3.2 Treatment

Three different pre-treated materials are assessed; chips, pellet and torrefied pellets. Production of these materials can be done with several different raw material inputs, where the production input of the feedstocks discussed above are the focus in this study. Biomass is pre-treated to make an upgraded homogenous fuel with several advantages: reduced storage, transport and handling costs, reduced plant investment and maintenance, and reduced impurities in the fuel (Loo and Koppejan, 2007).

Feedstocks can be chipped, or comminuted, to increase the bulk density of the fuel, and chips are mainly produced from saw residues and forest resources in Norway today (KLIF, 2001). The most common comminution devices are the disc and drum chippers (Andersson et al., 2002; Loo and Koppejan, 2007), see Figure 6. The disc chipper consists of a heavy rotating disc and two to four knives, while the drum chipper is made up of a rotating drum also with two to four knives embedded. The advantages of the disc chipper are the fairly uniform size of the produced chips and the possibility to adjust the chip size. The cutting angle of the drum chipper changes with the diameter of the tree and the device can reach high productivity, but the produced chips are less uniform and the maintenance costs are high.

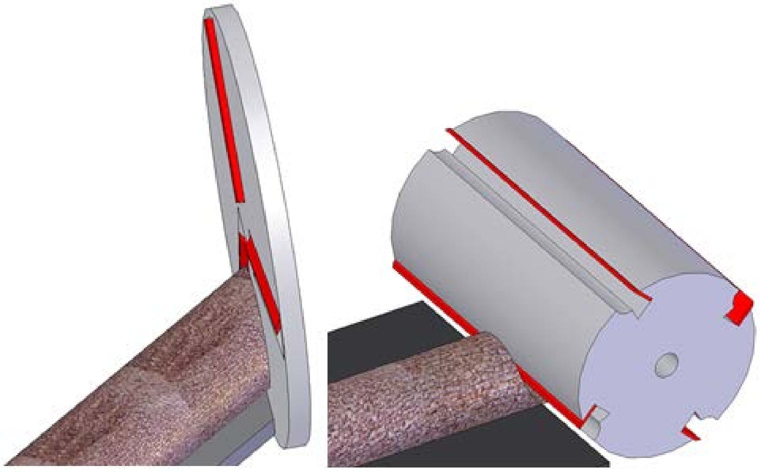

Figure 6: disc and drum chipper respectively (Ireland's Natural and Renewable Energy Source, 2006)

In addition to technology, at what time in the value chain chipping takes place is crucial (Andersson et al., 2002). Chipping is recommended to take place shortly before consumption, as processing to chips decreases the durability under storage. Generally, the closer to plant comminution is performed, the more cost-efficient it is. Dry matter losses can be high for chips, which leads to carbon and energy losses and also emissions of greenhouse gasses. There might also be problems of self-ignition during storage, particularly if the moisture content is high, as moist materials hold a higher temperature longer than dryer materials (Thörnqvist, 1985). Chipping off-road at logging site, chipping at landing (by forest road), or chipping at terminal or combustion plants are the value chain options for chipping (Andersson et al., 2002). If off-road chipping or chipping at landing is chosen, the chipper is often mounted on either the forwarder or truck respectively. Instead of such mobile chippers, stationary chippers can also be used. Stationary chippers are the most common at terminal or heating plants, and the system is in such cases referred to as *centralised chipping*. A centralised comminution choice can offer cost savings of two-thirds compared to off-road chipping at logging site, offering therefore also an economy of scale. Today, most chipping in the Nordic countries takes place at either landing or off-road in forest. Any system can offer the possibility to *chip on demand*, and the flow of chips is slowed down in periods with low demand. The biomass is then stored prior to chipping, and this reduces the storage losses.

As chips, also pellets are normally produced from saw residues and forest wood, but both chips and pellets are also produced from waste wood (Langerud et al., 2007). Pellets are used both in industrial combustion units and household pellets stoves, where only the industrial option is assessed in this study. The production of pellets in Norway peaked in 2006, but there has been an increase in pellets sales ever since – mainly because of increased imports, and to some extent due to lower export (NOBIO, 2010). The pellet prices have also increased quite substantially from 2004 to 2010, both for pellets sold in smaller units, bigger units and bulk. Pellets sold in bulk have experienced the highest increase in sale, partly as a result of new industrial pellet combusting units. Globally, Sweden and Canada are the biggest actors in the pellet market, and Canada is exporting pellets to Europe (Langerud et al., 2007). Both pellets and torrefied pellets (discussed below) are materials suited for transport as the heating value is high and the moisture content is low compared to untreated wood. This means that the material transported is optimised, as no excess water is transported and the energy transported per weight is high.

Figure 7 shows the production flow for the pelletising process. There are five main steps in this process: drying, milling, conditioning, pelletising and cooling (Loo and Koppejan, 2007). The raw material entering the pelletising process must have a constant and low moisture content – between 8 and 12 wt%, and this takes place in the drying process. In the milling step, the particle size is reduced – this step is also therefore referred to as size reduction, and a homogenous material is the result. Conditioning, or steam pre-conditioning, is performed to improve the adhesion by use of steam, causing a thin layer covering the particles. The dry, milled and pre-processed raw material then goes through pelletising, or densification, and the hot pellet is finally cooled to ensure durability.

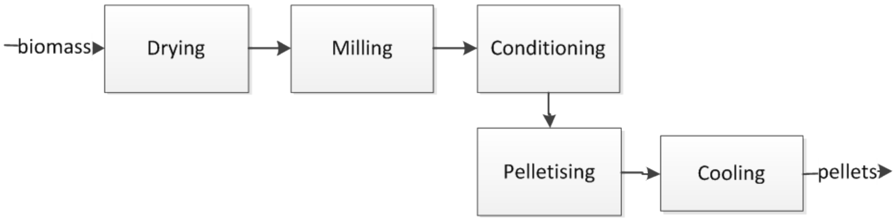

Figure 7: pelletising process flowchart (Loo and Koppejan, 2007).

As wood pellets have become a proven and mature technology, the combined torrefaction and densification process has been developed, i.e. producing torrefied pellets (TOP) in an integrated production chain (Bergman, 2005). Compared to conventional pellets, TOP have a higher heating value, lower moisture content and improved durability. This means that torrefied pellets are even more suitable for long-distance transport than what is the case for wood pellets, and TOP are also hydrophobic (i.e. water resistant). Torrefied pellets are also more flexible than regular wood pellets regarding feedstock type, as any fibrous material can be used, including any local supply source (ECF et al., 2010). The TOP process has a very high efficiency, about 96 %, but both capital investments and energy use during treatment are higher compared to conventional pellet production. The torrefaction process is a thermochemical process in the 200 to 300 °C temperature range and takes place at atmospheric conditions in the absence of oxygen. The residence time is short, typically 10-30 minutes. The biomass partly decomposes in the torrefaction process and the resulting product is a solid coal-like compound. TOP can even be stored together with coal and used in existing coal-fired power stations.

Figure 8 shows the production process and net energy flows for the TOP process. Before the actual torrefaction process takes place, drying of the biomass is required (Bergman et al., 2005). The values in Figure 8 are representative for a moisture content reduction from 50 % to 15 %. Typically, 70 % of the original biomass weight is retained in the solid product, and this product contains 90 % of the original energy. The remaining 30 % of the mass is converted to torrefaction gas, and this gas does not contain more than 10 % of the initial energy (on LHV bais). Based on these values, the energy densification is 130 % on a mass basis, and this is the main advantage of the torrefaction process. The densification itself takes place after cooling and size reduction of the torrefied biomass. The torrefaction and densification is in fact taking place in two distinctive process steps.

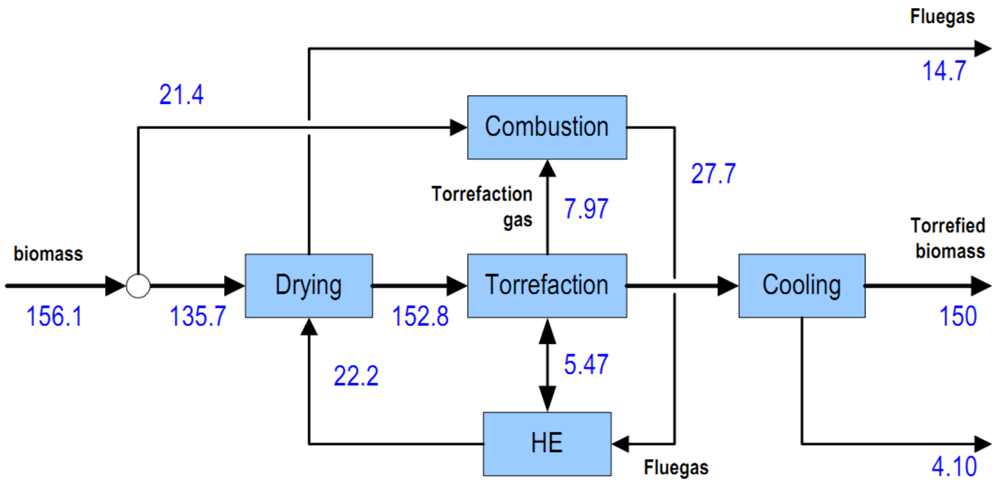

Figure 8: net energy flows [MW_{th}] for the TOP process (Bergman et al., 2005, p. 38)

3.3 Energy conversion

There are several energy combustion technologies available and four different options are analysed: combined heat and power (CHP) plant, district heating plant, boiler producing steam and thermal power plant producing electricity. The technologies are discussed below.

Larger, new power plants employ fluidised bed combustion (FBC) technology, which has the ability to combust materials of uneven particle size and moisture contents, and the ability to burn low-grade fuels (Hakkila, 2003). A steam turbine is used in both the thermal power plant producing electricity and in the CHP plant producing electricity and heat (Loo and Koppejan, 2007). Heat is produced in the combustion unit, generating steam in a boiler, which delivers mechanical power to run an electricity generator. Condensing plants are dedicated to electricity-only production, while the CHP plant also utilises the produced heat. CHP plants are internationally, and also in Norway, contributing to a further development of the use of bioenergy, as the integrated heat and power production results in a higher total efficiency than a stand-alone electricity plant (Langerud et al., 2007). The introduction of green certificates can also contribute to new investments in CHP plants.

Both CHP plants and thermal power plants utilise the *exergy* in biomass, where exergy refers to the ability to produce power (Langerud et al., 2007). In Norway there is an almost unlimited potential for power production, as the Norwegian electricity market is integrated with the common Nordic power market. This means that the Nordic electricity market can consume excess electricity produced in Norway.

Bioenergy therefore has the possibility to replace electricity produced from fossil fuels in other Nordic countries. A condensing power plant producing electricity can achieve an electric efficiency of 40-45 % (Hakkila, 2003; KanEnergi, 2007), also reported in the 35-40 % range (Gustavsson, 1997; IEA, 2007a). The utilisation of heat in a steam turbine plant reduces the electrical efficiency by about ten per cent (Loo and Koppejan, 2007), and CHP plants have an overall efficiency of 85-90 %, where the electric efficiency is 20-30 % and the heat efficiency is 55-70 % (Hakkila, 2003).

Biomass can also be combusted in district heating systems producing and distributing heat, and in such heating plants, an efficiency of 85-88 % can be achieved (Gustavsson, 1997; Hakkila, 2003; Loo and Koppejan, 2007). The Norwegian Government has a focus on district heating, and district heating can contribute to the goals of increased use of biomass for heat (Langerud et al., 2007). The advantage of district heating plants are centralised biomass combustion, so that conversion efficiency is higher, gas cleaning is less expensive and the ash handling is more effective than what is the case for household use of biomass. District heating plants are particularly interesting in areas with access to waste heat, inexpensive biomass fuel or waste, and in areas with high consumption density.

In addition to heat and electricity production, steam production in a boiler is assessed. The steam is utilised in industrial processes, mainly by the wood processing industry (Langerud et al., 2007). Such steam producing units have an efficiency of 89 % (Broek et al., 1996; CenBio, 2011). Steam can also be produced in a co-generating extracting steam cycle together with electricity (Bain et al., 1998), but in this thesis, steam production is modelled separately from electricity production.

3.4 Energy distribution

Three energy services are assessed in this study, i.e. electricity, heat and steam. Generally, the purpose of energy distribution is to distribute energy from a central energy generating unit to the consumer. Power systems have both a supply (producing) side and a demand (consuming) side (Wangensten, 2007). The link between the supply and demand sides are described in this section. Distribution generally consists of four phases: production of infrastructure, construction of infrastructure, use of distribution network and post-treatment of the network (Fröling and Svanström, 2005).

On a macro level, electricity consumption depends on income, or GDP, and historically electricity consumption has followed GDP very closely. Norway’s electricity market is part of the common Nordic electricity market, where Statnett is the system operator in Norway. Statnett is thereby responsible for security of supply, and also operates the high-voltage transmission grid. The Norwegian grid is made up of this transmission grid, as well as a high-voltage and a low-voltage distribution grid. The latter two are operated by local energy companies, whose responsibility includes operation, maintenance and new investments in the distribution grid. Infrastructure and operation of the electricity grid cause environmental impacts, important in a life cycle perspective.

In Northern-European countries heat is utilised in buildings for space heating and hot water generation (Fröling and Svanström, 2005). Hot water is the heat carrier, with the necessary piping infrastructure often underground. Material use, excavation and construction needs all imply environmental impacts. Overall, district heating has a high potential if used in office and apartment buildings with already existing central heating systems. The existing piping in the buildings can then be connected to the district heating piping network, and oil use in central heating systems is eliminated. Figure 9 shows a schematic diagram for hot water distribution; the thermal production plants are connected to a transmission line, which is connected to the distribution line. The distribution network transports hot water to consumers, who have a central heating system in their building connected to the distribution line.

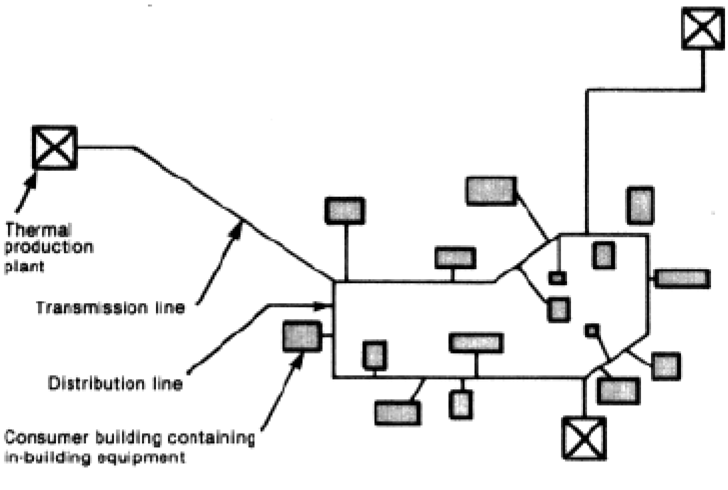

Figure 9: schematic presentation of a district heating network.

The third and final energy service assessed is steam. As mentioned above, steam is utilised by industries, and steam can be distributed in district heating networks (Langerud et al., 2007). The steam producing boiler would normally be located near the steam consuming industries, and the distribution network given in Figure 9 would be similar, but smaller – i.e. fewer consumers located closer to the thermal production plant.

4 PROCESS LCA OF NORWEGIAN BIOENERGY

There are several different value chains for bioenergy production in Norway. The different value chains are a sum of material, processing, technology and transportation. For the work carried out in this thesis, all the value chains investigated are split in six different steps: (1) feedstock, (2) transport to pre-treatment site, (3) pre-treatment, (4) transport to energy conversion site, (5) energy conversion and (6) energy distribution. Figure 10 presents the overall system, and the figure shows that there are six different feedstocks considered, seven different pre-treatment options, five energy conversion technology options, three energy services delivered to the market, and two transportation distances. All these materials and technologies are discussed in the theory chapter, and this chapter will present the LCA model, with focus on model assumptions and life cycle inventories (LCI).

The work carried out in this thesis is based on the work carried out the fall 2011 for the master project at NTNU. This project assessed the environmental impacts of two bioenergy value chains: chipped forest stemwood and torrefied pellets (TOP) from stemwood. Both materials were assumed to be combusted in a large-scale (100 MW_{el}) CHP plant. The environmental impact was assessed using LCA, with 1 kWh as the functional unit. The systems were case-specific to Norwegian conditions, and this is also the case for this thesis. The units in this work are assumed to be located in the Oslo area – an assumption that only affects the assumed total transport distance. The non-mountainous regions in the eastern parts of Norway also have the highest potential for increased forest harvest (Vennesland et al., 2006). This area is in addition the most populated area in Norway, and biomass fired power plants in the scale analysed in this assessment will most likely be located in the greater Oslo area – Eastern-Norway.

The six different process steps presented above each make up one of the six foreground matrices. The foreground matrices, representing the foreground systems, are put together in one final foreground system. This is performed in Matlab, and the LCA calculations are also done in this program. Table 80 and Table 81 in appendix 7 give the Matlab scripts used to run the calculations. Generally, each of the sub-foreground systems are put together from flowcharts presented for each step below. There are overall more processes in the foreground matrices than in the flowcharts, but these additional processes are mainly dummy processes converting units or included to ease the overall calculation. The foreground matrices are given in appendix 6, see Table 58 to Table 79. Transport is modelled using the *receiver input* (Strømman, 2010) method throughout the assessment, referring to the fact that the transport processes do not have any foreground process inputs.

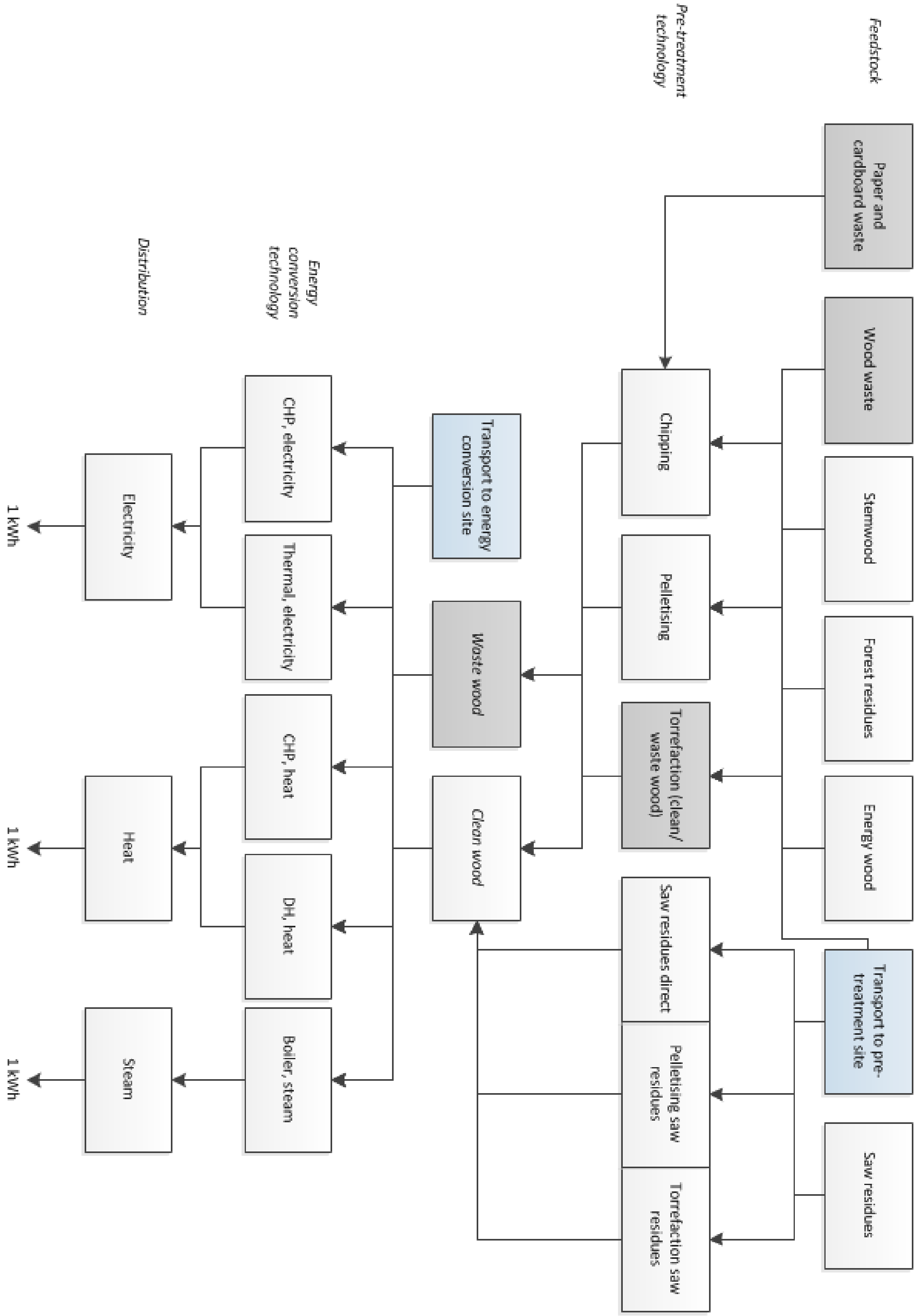

Figure 10: overall system flowchart

4.1 Feedstock

A total of six feedstocks are investigated in this assessment, them being stemwood, forest residues (FR), energy wood, sawmill residues (SR), paper and cardboard (P&C) waste and wood waste. In this section, each of these raw materials will be discussed together with theory, including the most important characteristics and life cycle inventories.

The different raw materials presented above can be classified by their origin (Alakangas, 2005); stemwood, energy wood and forest residues originate from forest, saw residues originate from the wood processing industry, while P&C and wood waste are used wood types. Figure 11 presents the feedstock flowchart for the different resources, as well as showing the differentiation between forest, wood processing and waste resources. The different feedstocks will be discussed below, starting with forest resources, resources from wood processing and waste following.

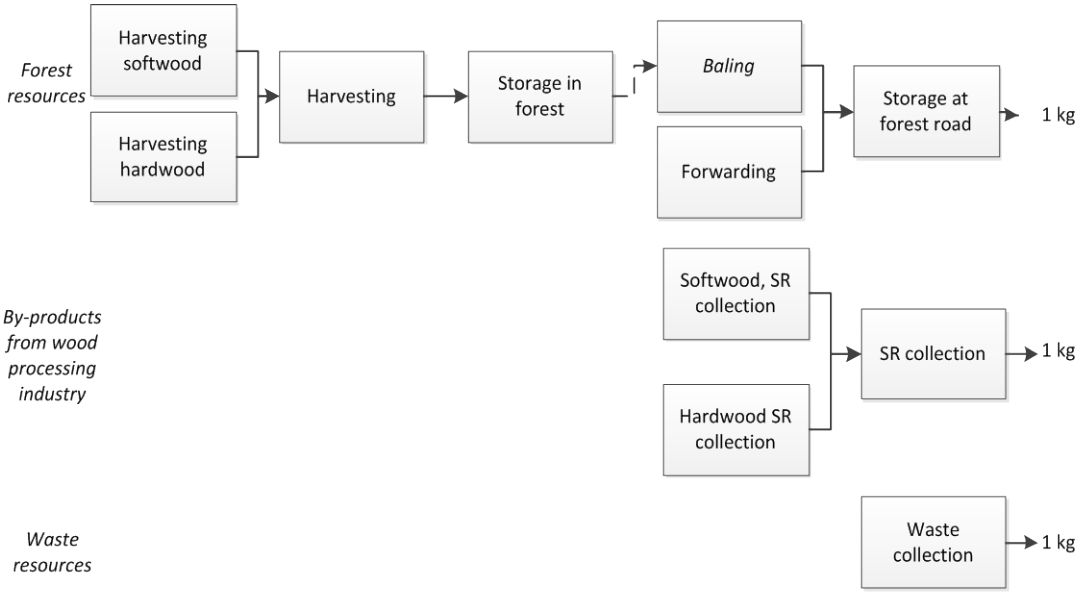

Figure 11: flowchart for the feedstock step.

There are several important characteristics of biomass feedstocks; moisture content, heating value and densities (Alakangas, 2005). Also ash percent, ash composition and carbon/hydrogen content are of importance. Only the former three will be discussed. The moisture content of fresh wood fuels varies between 40 and 60 %, and varies seasonally and differs in the different parts of the wood, wood species, age and growth site (Alakangas, 2005). Drying of biomass offers a potential thermal efficiency improvement, as the heating value increases (Loo and Koppejan, 2007).

The net calorific value, or the lower heating value, of dry matter varies between 18,3 and 20,0 MJ/kg for wood fuels (Alakangas, 2005). This value depends on what part of the tree which is in question – for instance needles and leaves have a higher heating value than the stem. Also densities vary, in particular between species, wood types, stands and age (Alakangas, 2005). Both the heating values and densities vary with moisture content.

Figure 11 presents the value chain for the feedstocks. Stemwood, forest residues and energy wood have the same principal feedstock value chain; harvest, storage in forest, forwarding and storage at road side. Baling is also included in the forest residue case. All forestry resources and their feedstock value chains will be discussed below. The feedstock value chains for saw residues and waste resources are discussed after. The most important characteristics are presented before assumptions and inventories are discussed.

Table 4 presents the moisture contents, densities, heating values on a wet basis and heating values on a dry basis for the three forestry resources assessed. The heating values are calculated from equation 16 and 17 in appendix 1, while the densities are calculated from the oven dry densities in equation 15. Both oven dry densities and heating values for the resources are given in appendix 1 together with the equations. The heating values and densities depend on these oven dry values and also on the moisture contents. The moisture contents for the stemwood and energy wood cases are assumed to be the same, and the first reduction in moisture content in the feedstock value chain takes place while the biomass is stored in forest (Forsberg, 1999; Loo and Koppejan, 2007; NOBIO, n.d.). The second moisture content reduction takes place at forest road, and each reduction step reduces the moisture content by ten per cent – i.e. from 50 % to 30 % overall. The forest residues case differs; the biomass is stored in forest for the entire moisture reduction. The total moisture content reduction is the same as the two other forest resources, only at what time in the value chain the reduction takes place differs (Alakangas, 2005). The different process steps are discussed more thoroughly below.

	MC []			**$W_{em,wb}$ [MJ/kg]**		
	Stemwood a)	Forest residues b)	Enery wood a)	Stemwood	Forest residues	Energy wood
Harvest	0,5	0,5	0,5	8,38	8,47	8,47
Storage in forest	0,4	0,3	0,4	8,33	12,8	10,6
Baling	-	0,3	-	-	12,8	-
Forwarding	0,4	0,3	0,4	10,55	12,8	10,6
Storage at forest road	0,3	0,3	0,3	10,50	12,8	12,8
	Density [kg/m3]			**$W_{em,db}$ [MJ/kg]**		
Harvest	857,8	160,0	808,6	16,8	16,9	16,9
Storage in forest	714,8	114,3	673,8	16,7	18,3	17,7
Baling	-	157,1	673,8	-	18,3	-
Forwarding	714,8	157,1	-	16,7	18,3	17,7
Storage at roadside	612,7	157,1	673,8	17,5	18,3	18,3

Table 4: moisture contents, densities on a wet basis, and heating values on LHV, dry and wet basis for the forestry feedstocks.

a) (Forsberg, 1999; Loo and Koppejan, 2007; NOBIO, n.d.)

b) (Alakangas, 2005)

The efficiencies throughout the value chains are crucial, as these represent the losses in the value chain. Table 5 gives the efficiencies for the feedstock value chain. The harvesting efficiency is 98 % for both stemwood and energy wood harvest (Forsberg, 1999), while the harvesting efficiency is 100 % for forest residues. Forest resources are a by-product of stemwood harvest, and it is therefore assumed that harvest losses can be neglected. Stemwood and energy wood have further losses while stored in forest and when forwarded, both processes have 2 % mass losses (Forsberg, 1999). Forest residues have an 85 % efficiency while stored in forest (Forsberg, 2000), as needles, leaves and some bark and branches fall off. This reduces the efficiency, but is crucial for nutrient recycle. Following, both baling (more below) and storage at forest road have an efficiency of 98 % for the forest resources case. Stemwood and energy wood have a 100 % efficiency while stored at landing.

Efficiency			
	Stemwood [a)]	Forest residues [b)]	Energy wood [a)]
Harvest	0,98	1	0,98
Storage in forest	0,98	0,85	0,98
Baling	-	0,98	-
Forwarding	0,98	1	0,98
Storage at forest road	1	0,98	1

Table 5: efficiencies throughout the feedstock value chain for the forestry resources.
[a)] (Forsberg, 1999)
[b)] (Forsberg, 2000)

Harvesting of stemwood, forest residues and energy wood are all divided in two processes: harvesting softwood and harvesting hardwood, see Figure 11. Table 3 in the theory chapter gives the hardwood and softwood fractions for forestry in eastern parts of Norway, and these fractions are used for all forestry resources. Harvesting efficiencies and moisture contents are given in Table 5 and Table 4 respectively. The losses do not imply carbon dioxide emissions in the harvesting step.

The inventories for stemwood harvest are a combination of the two Ecoinvent processes *industrial wood, Scandinavian softwood, under bark, at forest road* and *industrial wood, Scandinavian hardwood, under bark, at forest road* (Jungbluth et al., 2007). The harvesting inventories for energy wood harvest are based on the Ecoinvent processes *residual wood, softwood, under bark, u=140%, at forest road* and *residual wood, hardwood, under bark, u=80%, at forest road*. Since these Ecoinvent processes are for wood *at forest road*, the forwarding distance assumed (more later) is subtracted. The harvesting processes represent modern average technology in Scandinavia (Jungbluth et al., 2007), and all have inputs of the process *power sawing, without catalytic converter*. The diesel consumption in the power sawing processes is updated according to Skog Forsk (2006). See appendix 2 for the diesel inputs and emissions values applied for harvest in this study.

Forest residue harvest is a by-product of stemwood harvest, and these two cases have the same inputs. An allocation for both stemwood and forest residue harvest is therefore integrated. This allocation is a mass based allocation, based on biomass expansion factors (BEF). The BEFs present the dry matter mass over volume, and converts tree component (e.g. stem) volume to whole tree mass (Lehtonen et al., 2004). The BEFs used are dependent on both stand age and species. A rotation period of 100 years for stemwood is applied, the mass of forest residues and stemwood are found, and the allocation factor is calculated from the share of stemwood/FR mass to the sum of both. Appendix 3 presents calculations and assumptions for the applied BEFs.

After the forest biomass is harvested, both stemwood, energy wood and forest resources are assumed to be stored in forest. This is both to reduce moisture content and to allow nutrient recovery for the forest residues case. Raw biomass storage will result in losses, and therefore also emissions. Table 4 and Table 5 show moisture contents, densities, heating values and losses for this storage process. 98 % efficiency indicates 2 % dry-matter loss, and the carbon in the dry matter is assumed to be emitted as CO_2 emissions, calculated from equation 11. The forest residues stored in forest have an efficiency of 85 %, which includes the losses of e.g. needles. As stated before, this reduces the recovery rate, but contributes to the forest nutrient recovery. There are no emissions for forest residue storage in forest, as was the case for losses from harvest. These losses are rather *operational* losses, reducing the process efficiency.

Before the forest residues are forwarded to forest road, the residues are baled. Baling increases the density and therefore contributes to more efficient handling, storage and transport (Hoyne and Thomas, 2001). The baling is modelled using the Ecoinvent process with the same name (Nemecek and Kägi, 2007). The baling process has an efficiency of 98 % (Forsberg, 1999), where the dry-matter losses cause carbon dioxide emissions calculated from equation 11.

Forwarding from harvest site to forest road has an assumed distance of 500 metres, and the transportation process applied is *transport, tractor and trailer* (Jungbluth et al., 2007). Forwarding can also be performed by other means than tractor, and Yrjöla (2001) reports that 70 % of the forwarding is performed with forwarders, 25 % with tractors and the rest by other means. Forwarding distance is discussed in literature, and Table 6 shows an overview of the forwarding distances assumed by two sources. Eriksson and Gustavsson (2008) indicate three forwarding distances, with an average of 462 metres, and Yrjöla (2001) reports five ranges of distances. The forwarding distances in Eastern-Norway tend to be lower than for regions in Northern-Norway, so when assuming that the longer than 2 kilometres forwarding distance is not applicable for this specific case, the average distance for Eastern-Norway is 561 metres. Combining these two values gives an average forwarding distance of 512 metres. Based on this, and the fact that 500 metres is the assumed forwarding distance by Skog Forsk (2006), 500 metres is the applied forwarding distance in this assessment.

The efficiency of the forwarding process is as stated in Table 5 to be 98 %, which means there are 2 % losses (Eriksson and Gustavsson, 2008; Forsberg, 1999). Diesel use and emissions for the forwarding process are updated according to data from Skog Forsk (2006), see Table 35 in appendix 2. There is not applied any difference between forwarding of stemwood, baled forest residues or energy wood.

Eriksson and Gustavsson (2010)			*Yrjöla* (2001)		
Distance		**Fraction**	**Distance**		**Fraction**
< 400	m	0,65	1-199	m	0,24
			200-499	m	0,27
400-700	m	0,9	500-999	m	0,25
> 700	m	0,49	1000-1999	m	0,17
			> 2000	*m*	*0,07*

Table 6: forwarding distances.

After the biofuel is transported to road side, storage at landing takes place. This is the final step for the forest resources in the feedstock value chain. The biomass is assumed to be transported from this storage process at a moisture content of 30 %, implying a moisture content reduction of 10 % for stemwood and energy wood. This reduction will impact both the density and the heating value, as can be seen from Table 4. Also, there are no mass losses for stemwood and energy wood for the storage at road side process – i.e. 100 % efficiency (Forsberg, 1999). The baled forest residues have no moisture content reduction, but there are 2 % dry-matter losses (Forsberg, 2000), and as before, these imply carbon dioxide emissions calculated from equation 11.

For resources from both wood processing industry and waste (see Figure 11), collection of resources is the only process step. Table 7 presents the moisture contents, densities on a wet basis, and heating values on a wet and dry basis. Heating values and densities are as before calculated from equation 15, 16 and 17 in appendix 1, where the oven dry values also are presented. Neither saw residues, P&C waste nor wood waste have a moisture content reduction in the feedstock step. Saw residues have a moisture content of 15 % at collection (AEBIOM, 2008; Wilén et al., 1996), while the waste resources have a moisture content of 10 % (Miles et al., 1996). Table 8 shows the efficiencies for the waste flow value chains. The collection efficiency is assumed to be 98 % for saw residues, P&C waste and wood waste.

	MC [%]			$W_{em,wb}$ [MJ/kg]		
	Saw residues a)	P&C waste b)	Wood waste b)	Saw residues	P&C waste	Wood waste
Collection	0,15	0,1	0,1	15,8	18,6	20,1
	Density [kg/m3]			$W_{em,db}$ [MJ/kg]		
Collection	176,4	156,7	181,1	18,6	20,5	22,0

Table 7: moisture contents, densities on a wet basis, and heating values on a LHV, wet and dry basis for saw residues, P&C waste and wood waste.
a) (AEBIOM, 2008; Wilén et al., 1996)
b) (Miles et al., 1996)

	Efficiency		
	Saw residues	P&C waste	Wood waste
Collection	0,98	0,98	0,98

Table 8: feedstock efficiencies for saw residues, P&C waste and wood waste.

For the residues from the sawmill industry, collection is divided between softwood and hardwood collection – as also was the case for forest harvest. The hardwood/softwood fraction *for sale* is used rather than share of species standing in forest. This fraction is quite different, as the hardwood fraction sold to industries is very low in Norway – only 1 % (Rognstad and Steinset, 2010), as discussed in the theory chapter. The residues from hardwood are modelled from a softwood process, as no hardwood process is available. The wood input is corrected to hardwood rather than softwood, and the *softwood, allocation correction* process is changed to *hardwood, allocation correction* (Jungbluth et al., 2007). These processes are incorporated to correct the carbon balance for products with a low economic value.

Saw residues is a collective term in this study, pointing to sawdust and chips from the sawmilling industries. Therefore, the collection is a combination of the two Ecoinvent processes *sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant* and *chips, Scandinavian softwood (plant-debarked), u=70%, at plant* (Hischier, 2007). 11 % of the saw residues are sawdust, while 88 % of the saw residues are chips from the saw industry (Tellnes et al., 2011). As for the stemwood/forest residue case, allocation is also applied for saw residues; saw residue is a by-product from the sawn timber production, and economic allocation is used. The process-integrated, Ecoinvent economic allocation factor is applied (Hischier, 2007), i.e. no change in the assumed allocation factor.

The waste collection of P&C and wood waste are modelled using the ETH-ESU 96 unit process *infra municipal waste collection per kg* (Frischknecht and Jungbluth, 2004). This process includes only the infrastructure associated with waste collection, with no transport inputs and associated emissions. Transport is included in the transport to pre-treatment site step discussed below. For the waste products, no impacts past collection are included, and no allocation is applied.

4.2 Transport to pre-treatment site

The forest feedstocks are transported to the pre-processing site after storage at forest road, while the waste and wood processing resources are transported from collection site to pre-treatment site. This is *one of two* transport distances in the overall system. The total transport is split in two separate distances: the first from forest road/collection site to pre-treatment site, and the second from pre-treatment site to combustion site. A total transport distance of 160 kilometres is assumed (see below) for the forest resources, where 25 % of the total transport distance is assumed to take place from forest road to pre-treatment site, i.e. 40 kilometres. The assumed distance to pre-treatment site for the waste resources is assumed lower, as the waste facilities are considered to already be centralised (unlike landing at forest road). Therefore, the transport distance to pre-treatment site is assumed to be 20 kilometres for the waste and wood processing resources. The total transport distance for the waste resources and saw residues is therefore assumed to be 140 kilometres. Pellet and TOP production takes place at the pre-treatment site, while chipping and saw residue storage is assumed to take place at the energy conversion site. Therefore, the transport distances for the chips and direct saw residue cases are assumed to be zero in this transport step. Table 36 in appendix 4 shows the vector used to calculate the foreground value for this step. This vector is multiplied by the only foreground value for this transport step, see transport to treatment site foregronund matrix in table Table 63 in appendix 6.

The total transport distance of 160 kilometres is based on calculations; Table 9 shows the average transport distance assumed for each county in Eastern-Norway, which is found from calculations using a map and finding the driving distance from available distance calculators. The combustion site is, as stated earlier, assumed to be located close to the Oslo area, and a radius of 15 km is found for Oslo County. The distance for each of the counties is calculated from what is thought to be the centre of each county to the 15 km border of Oslo County. Whether Telemark is included or not, the average transport distance is 160 km. The Ecoinvent transport process used is *transport, lorry >16t, fleet average/ RER* – see Table 44 in appendix 5 for inventory for this transport system.

	Distance to site		Fraction [a)]
Østfold	70	km	0,091
Akershus	30	km	0,103
Hedmark	220	km	0,005
Oppland	230	km	0,398
Buskerud	120	km	0,181
Vestfold	90	km	0,165
Telemark	160	km	0,058

Table 9: transport distances to the Oslo and harvesting fractions are for each county at "Østlandet", Norway.

[a)] (SSB, 2011c)

There are many uncertainties in the calculations of average transport distance, e.g. not finding the correct centre of each county, incorrect calculations of distance from available distance calculators, an uneven distribution of forest land in the counties, etc. The transport distance is close to values indicated in literature; an average transport distance assumed for Norwegian industry in LCAs is 120 kilometres (Michelsen et al., 2008). Taken into consideration that this specific case is of quite a large scale, a longer distance for this assessment can be expected.

4.3 Pre-treatment

Seven different pre-treatment options are investigated: (1) chipping, (2) pelletising, (3) torrefaction of clean wood, (4) torrefaction of waste wood, (5) saw residues direct, (6) saw residues pelletising and (7) saw residues torrefaction. The last three options are separated from the first three because the saw residues have no comminution need prior to pre-treatment – as is the case for the other feedstocks. Figure 12 presents the treatment flowchart.

The transported feedstocks are stored at the pre-treatment facility, but as no losses will occur for the untreated feedstock (Forsberg, 1999), the storage process is not included in the model. No losses imply 100 % efficiency and no storage emissions. Figure 12 shows that the untreated feedstocks are chipped, and the chips can be the final, treated product or the chipped material can be either pelletised or torrefied. The saw residues on the other hand are not chipped. These can be stored – which implies no further treatment, or the residues can be pelletised or torrefied. If one of the last three options mentioned above is chosen the chipping is not required, as saw residues are a combination of sawdust and chips. The pelletising and torrefaction technologies are identical for the saw residues and the other feedstocks, but exclude the chipping process. Therefore, there are *four* different end-products from the treatment step which will be discussed, i.e. chips, pellet, TOP and saw residues without any further treatment.

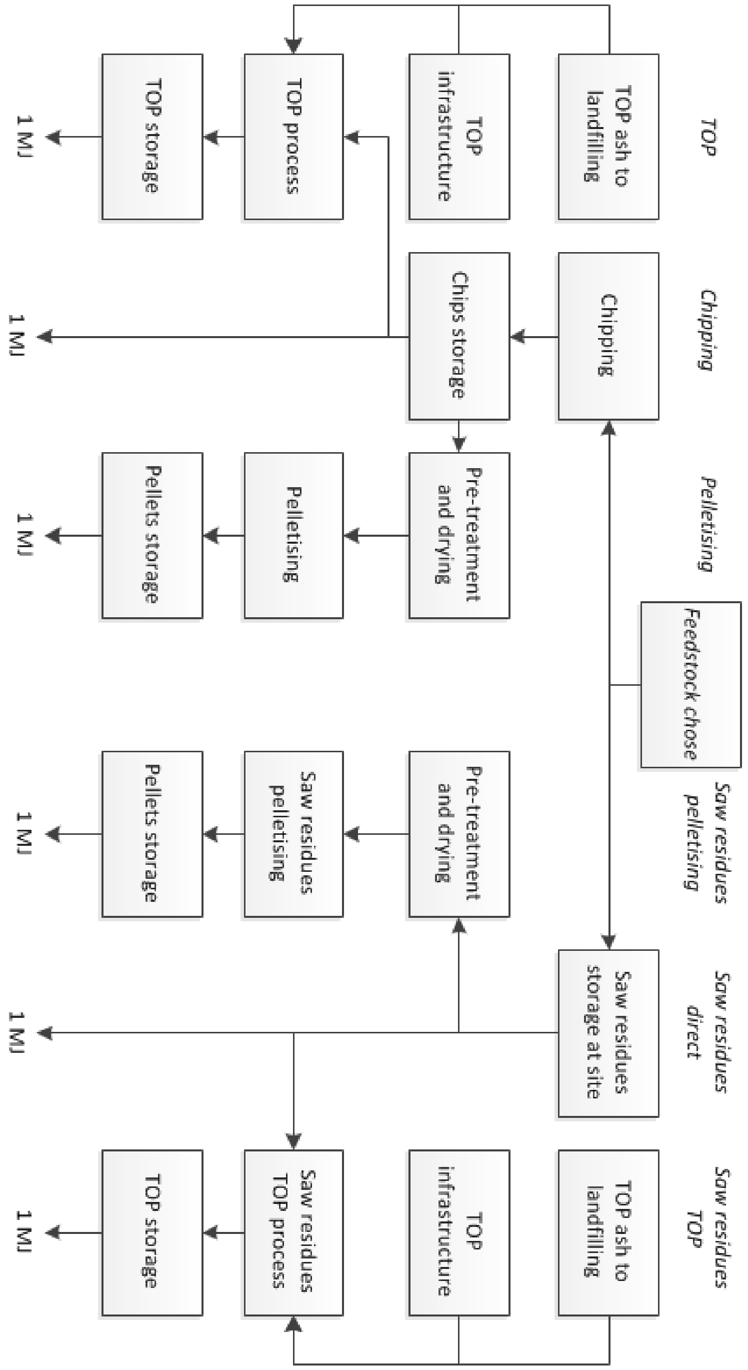

Figure 12: pre-treatment flowchart.

Table 10 presents the moisture contents, densities, heating values on a wet basis and heating values on a dry basis for the pre-treated materials. As for the feedstocks, calculations are based on equation 15, 16 and 17 in appendix 1, and the oven dry values are given in this appendix. The table below shows that the moisture content is lowest for TOP and highest for chips. A similar picture is seen for the densities and heating values, where TOP and pellets have the highest values. Higher densities and heating value is the reason to increase the level of treatment of the feedstocks, as a more effective material is produced for combustion.

	MC []				**$W_{em,wb}$ [MJ / kg]**			
	Chips [a]	**Pellets**	**TOP**	**SR**	**Chips** [e]	**Pellets**	**TOP**	**SR**
Chipping	0,3	0,3	0,3	-	12,2	12,2	12,2	-
Chips storage	0,3	0,3	0,3	-	12,2	12,2	12,2	-
Pelletising	-	0,1 [b]	-	-	-	16,9 [f]	-	-
Pellets storage	-	0,1 [b]	-	-	-	16,9 [f]	-	-
TOP	-	-	0,03 [c]	-	-	-	20,8 [g]	-
TOP storage	-	-	0,03 [c]		-	-	20,8 [g]	-
SR	-	-	-	0,15 [d]	-	-	-	15,8 [h]
	Density [kg / m3]				**$W_{em,db}$ [MJ / kg]**			
Chipping	259,1	259,1	259,1	-	17,7	17,7	17,7	-
Chips storage	259,1	259,1	259,1	-	17,7	17,7	17,7	-
Pellets	-	650	-	-	-	18,8	-	-
Pellets storage	-	650	-	-	-	18,8	-	-
TOP	-	-	800	-	-	-	21,4	-
TOP storage	-	-	800	-	-	-	21,4	-
SR	-	-	-	176,4	-	-	-	18,6

Table 10: moisture contents, densities on a wet basis, and heating values on a LHV, wet and dry basis for the pre-treated materials.

[a]

[b] (Loo and Koppejan, 2007; Sjølie and Solberg, 2011; Uslu et al., 2008)

[c] (Bergman, 2005)

[d] (AEBIOM, 2008; Wilén et al., 1996)

[e] (Loo and Koppejan, 2007)

[f] (Loo and Koppejan, 2007; Sjølie and Solberg, 2011; Uslu et al., 2008)

[g] (Bergman, 2005)

[h] (Wilén et al., 1996)

Table 11 shows the efficiencies for pre-treated materials at the different steps in the treatment value chain. The chips storage steps result in losses, while storage of pellets and TOP do not indicate any losses. As for chips, storage of saw residues also implies losses. The dry-matter losses result in greenhouse gas emissions, as discussed earlier in this thesis. Pellets and TOP can be stored without any losses.

Efficiency				
	Chipping	**Pellets**	**TOP**	**Sawdust**
Chipping	0,95 [a)]	0,95 [a)]	0,95 [a)]	-
Chips storage at site	0,983 [b)]	0,985 [b)]	0,985 [b)]	-
Pellets	-	1 [c)]	-	-
Pellets storage	-	1 [c)]	-	-
TOP	-	-		-
TOP storage	-	-	1 [d)]	-
Saw residues storage	-	-	-	0,95

Table 11: value chain efficiencies for the pre-treated materials.
[a)] (Eriksson and Gustavsson, 2010)
[b)] (Eriksson, 2011)
[c)] (Forsberg, 1999)
[d)] (Bergman, 2005)

Comminution can either be performed to produce chips for combustion, or as part of pellets and TOP production. The chipping process is modelled using the Ecoinvent process *industrial residual wood chopping, stationary electric chopper, at plant*, which includes the chopper infrastructure, electricity, oil and steel use, and emission of waste heat (Werner et al., 2007). The amount of wood chopping requested per volume chips is found using hardwood and softwood fractions together with the wood chopping inputs to the Ecoinvent processes for wood chips from forest, for hardwood and softwood, respectively. The electricity input to the chipping process is updated (Fantozzi and Buratti, 2010) and changed to present the Norwegian electricity market. Nordic rather than Norwegian electricity production is chosen throughout the assessment to represent the fact that Norwegian electricity consumption is part of a common Nordic electricity market.

The dry-matter losses from the chipping process is 5 % (Eriksson and Gustavsson, 2010), see Table 11. The sawdust losses from this chipping process could be used in agriculture and livestock farming, but all losses are assumed to stay at site. The dry-matter losses are emitted as CO_2 emissions, calculated from equation 12, but all carbon is assumed to be emitted as carbon dioxide.

After chipping, the chips are stored, and the dry-matter losses from chips storage depend on storage time. The treatment case producing chips as final product has the longest storage time; six weeks, while chips storage prior to pelletising or torrefaction is assumed to be only two weeks. It is assumed that prospective, further pre-treatment is performed as soon as possible and that storage takes place as pellets or TOP. Neither pellets or TOP have any dry-matter losses during storage (Bergman, 2005; Forsberg, 1999). Table 12 presents the dry-matter losses from chips storage for one to six weeks storage time. In addition to CO_2 emissions from dry matter loss, there will be emissions of N_2O and CH_4 from chips storage. Wihersaari (2005) gives the following emissions factors: 60 grams CH_4 m^{-2} day^{-1} and 1,2 grams N_2O m^{-2} day^{-1}, presented earlier in this thesis. The direct saw residues case have the same assumed storage time as the chipping case, and the same dry-matter losses and GHG emission values are incorporated.

Accumulated dry-matter losses for wood chips [%]				
1 week	2 weeks	3 weeks	6 weeks	7 months
1,1	1,5	1,6	1,7	11,3

Table 12: dry-matter losses for chips storage (Eriksson, 2011)

Pellets and TOP production both require chipping, as stated above. Starting with pellets production, prior to the pelletising process, the chips are pre-treated and dried, see Figure 12. This drying process is made up of an infrastructure unit used for the drying, as well as electricity use. The infrastructure unit used is the *industrial furnace, coal, 1-10 MW* process (Dones et al., 2007). The pelletising process itself is modelled similar to the pre-treatment process, and consists of an infrastructure unit and electricity use. The infrastructure unit is the Ecoinvent pelletising process called *wood pellet manufacturing, infrastructure/ RER*. Waste heat emissions from the pelletising process are assumed to be the same as pelletising processes available in Ecoinvent (Dones et al., 2007). The pellet process is presented in Figure 12 and in Figure 7 in the theory chapter, and the electricity use is modelled from Uslu et al. (2008).

For the torrefaction case, it is assumed a combined torrefaction and pelletising process, where the final product is referred to as torrefied pellets (TOP). Figure 12 presents the flowchart for the TOP case. Infrastructure need, the torrefaction process itself, ash handling from the torrefaction process and TOP storage will be discussed. Two TOP choices are available for the treatment case, one for clean wood and one for waste wood. Differences between the TOP clean wood and the TOP waste wood choices can be seen for the emission factors in the TOP process and TOP ash to landfilling process.

The infrastructure for the TOP choices includes two boilers, one for drying and one for the reaction in the torrefaction process. In addition, the infrastructure unit for pellets manufacturing is also included. The boilers are 1-10 MW furnaces for hard coal, which are assumed to represent the torrefaction process. The ash resulting from the TOP process is sent to landfilling, as is the case for the ash produced from combustion also. The inventory is the same for this process as for the ash processes resulting from combustion, and these are discussed in the energy conversion step below. Differences in assumptions are all visible in the foreground matrix.

Figure 8 in the theory chapter shows the net energy flows for the TOP process, and calculations are based on this figure. Before the torrefaction process, drying of the biomass takes place, and Figure 8 represents a case where a moisture content reduction from 50 % to 15 % takes place (Bergman et al., 2005). An important assumption made for the TOP process is that the energy flows in Figure 8 are independent of MC. This would in reality not be the case, but is assumed for this assessment. For the torrefaction case investigated in this study, the chips going to the TOP process are assumed to have a moisture content of 30 %. The final moisture content after the drying process is assumed to be the same as the case presented in Figure 8, i.e. 15 %. Therefore, the moisture content reduction is less for the case in this thesis, but this difference is not included in the calculations.

After the wood chip MC is reduced to 15 %, the biomass is sent to torrefaction. Before pelletising the biomass is cooled, and electricity input is included to model the pelletising step. The electricity need for this densification step is assumed to be the same as in the pellet case. Emissions from the clean wood TOP process are modelled with data from Nielsen et al. (2010) representing biomass producer gas. The torrefaction gas is combusted, as can be seen from Figure 8, and the combustion of this gas is assumed to have emissions that can be modelled as combusted producer gas. The NO_x emissions are much higher than the emissions from wood fired CHP plants and the emissions of unburned hydrocarbons (UHC) are much lower. Table 10 shows the MC, density and LHV assumed for the torrefaction process. Two changes are made for the waste wood TOP emissions; methane emissions are 14,3 % higher and N2O emissions are 60 % lower. These changes are based on the emission factors found for clean and waste wood in combustion emissions in the energy conversion step below.

After the integrated torrefaction and pelletising process, no losses occur. The high energy density pellets are water resistant and no biological degradation is assumed to occur; therefore these torrefied pellets are less of a hazard in anaerobic conditions compared to the wood chip alternative (Kiel, 2011). This is also why it is more desirable that torrefaction takes place early in the value chain, and that storage takes place in the form of TOP rather than wood chips. Pellets share these properties, although to a lower degree.

4.4 Transport to energy conversion site

The total transport distance is, as stated, 160 kilometres, which is split in two distances. The second transport step is from processing site to combustion site. For the pellets and TOP cases 75 % of the total transport distance is assumed for this step, i.e. 80 kilometres. For the saw residues direct and chips cases, the transport distance for this step is assumed to be zero. Chipping and saw residue storage is assumed to take place at energy conversion site. The same transport process is assumed for this transport step as for the transport step prior to this one. Table 37 in appendix 4 shows the vectors used to calculate the foreground value for this step.

4.5 Energy conversion

Five different energy conversion technologies are assessed: CHP with electricity demand, CHP with heat demand, thermal power plant producing electricity, district heating plant producing heat, and a boiler producing steam. In the performed analysis, there are a total of ten energy conversion options, where each conversion technology has the option of combusting clean or waste wood. The differentiation between clean and waste wood is done to incorporate the different emissions factors for both ash and combustion emissions. Figure 13 shows the energy conversion flowchart for the five energy technologies. Infrastructure, operational inputs and emissions, and ash handling and following emissions are discussed below together with the most important characteristics.

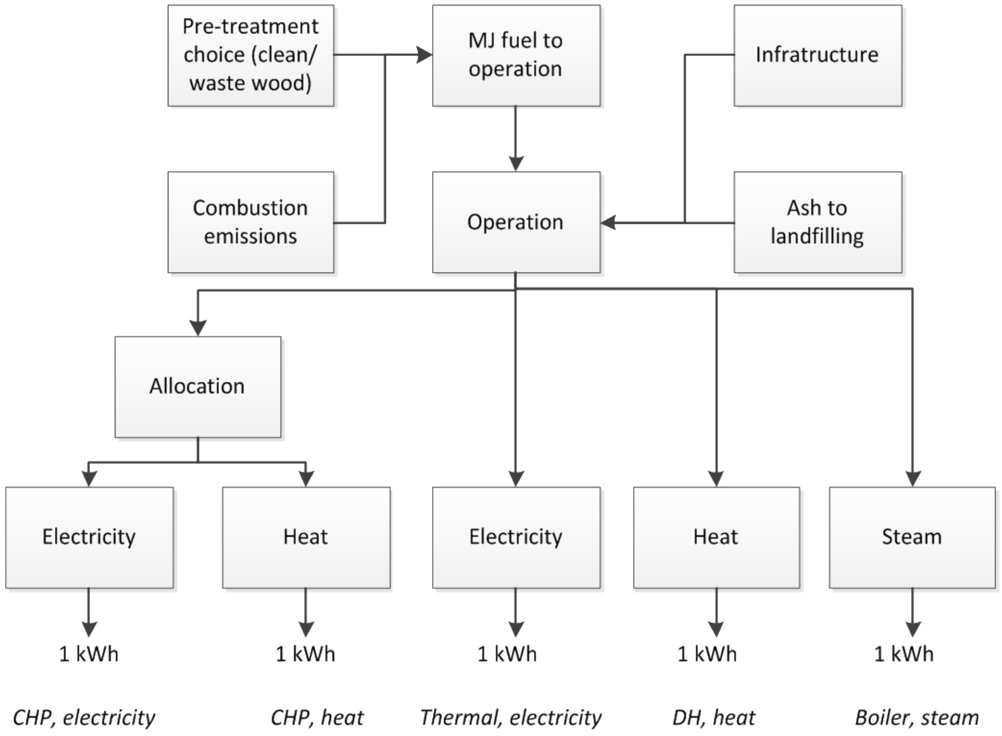

Figure 13: energy conversion flowchart.

The different energy conversion technologies are discussed in the theory chapter and assumptions will be presented here. For the conversion technologies, important characteristics include efficiency, capacity factor, total unit lifetime and capacity. Starting with the latter, the capacity for the five options is 50 MW for all. This is a quite high scale for Norwegian conditions, while compared to existing plants in Sweden and Finland considered a medium scale (KanEnergi, 2007). Examples of plants in Sweden and Finland are *Jämtkraft* in Sweden with a capacity of 110 MW_{th}, and *Allholmens Kraft* in Finland with a capacity of 240 MW_{el}, the latter thereby the biggest bio-fuelled power plant in the world. Also the capacity factor and lifetime are assumed the same for the five options. The capacity factor is the actual power output over the potential output if the plant had operated at design load, and is assumed to be 60 % for all options. The main reason for a reduced capacity factor is plant shut-down. The lifetime is assumed to be 25 years for all technology options (Dornburg and Faaij, 2001).

For electricity production in a 50 MW_{el} power plant, the electrical efficiency is chosen to be 30 % in cogeneration mode (CHP) and 40 % in the case of the condensing power plant (Loo and Koppejan, 2007). Heat production in cogeneration mode has a heat efficiency of 60 % (Hakkila, 2003), while the efficiency of the steam producing boiler is 89 % (Broek et al., 1996; CenBio, 2011). See Table 13 for these chosen efficiencies.

	η_{el}	η_{th}	η_{tot}
CHP, el	0,30[a)]	0,60[b)]	0,90[b)]
CHP, heat	0,30[a)]	0,60[b)]	0,90[b)]
Thermal, el	0,40[c)]	0	0,40
DH, heat	0	0,86[d)]	0,86
Boiler, steam	0	0,89[e)]	0,89

Table 13: electrical, thermal and total efficiencies chosen for the five energy conversion technologies.

[a)] (Hakkila, 2003; Loo and Koppejan, 2007)

[b)] (Forsberg, 2000; Hakkila, 2003)

[c)] (Gustavsson, 1997; Hakkila, 2003; IEA, 2007a; KanEnergi, 2007; Loo and Koppejan, 2007)

[d)] (Gustavsson, 1997; Hakkila, 2003; Loo and Koppejan, 2007)

[e)] (Broek et al., 1996; CenBio, 2011)

The infrastructure for each energy technology modelled is a medium scaled combustion plant of 50 MW. There is no suitable Ecoinvent process available for this scale, and the CHP plant and the thermal power plant producing electricity are modelled from the Ecoinvent process *hard coal power plant, 100MW/GLO/I U* scaling it down to 50 MW, while the district heating plant and the boiler are modelled from the Ecoinvent process *industrial furnace, coal, 1-10 MW/RER/I U* scaling it up to 50 MW. The reason why these processes are used rather than the available mini CHP and boiler infrastructure processes is that the mini CHP and boiler processes have very small scales compared to the model goal of 50 MW; 2 kW_{el} and 10 kW_{el} respectively. This leads to unrealistically high material inputs, and the chosen infrastructure processes are therefore more suitable. The scaling is performed using equation 13 (Searcy and Flynn, 2009), and an economy of scale factor of 0,7 for bioenergy plants is used. The factor is originally made for financial cost, but it is assumed that the same factor can be applied for material inputs.

$$M_2 = M_1 \left(\frac{Y_2}{Y_1}\right) * 0{,}7 \qquad (13)$$

Electricity input in the operation phase for the different technologies is modelled using data from two plants; Norske Skog and Hammargård (CenBio, 2011). The electricity use at Norske Skog and Hammargård is 27,7 and 14,4 GWh per year respectively. The former value is used for the modelling of the CHP plant and for the thermal power plant producing electricity, while the electricity use from Hammargård is used for modelling the district heating plant and the steam producing boiler. Table 14 shows the electricity use at the different conversion technologies.

	[MJ EorH / yr]	[kWh/MJ]	
CHP, el	$2,84*10^9$	9,74E-03	**Norske Skog*
CHP, heat	$1,42*10^9$	1,95E-02	**Norske Skog*
Thermal, el	$2,37*10^9$	1,05E-02	**Norske Skog*
DH, heat	$1,10*10^9$	1,31E-02	**Hammargård*
Boiler, steam	$1,05*10^9$	1,37E-02	**Hammargård*

Table 14: electricity use at the different energy technology options (CenBio, 2011).

Remaining operational inputs are oil for plant start-up, operation of wet scrubber and operation of selective catalytic reduction (SCR) unit. The wet scrubber is retaining SO_x in the flue gas, and the modelled operation of the unit includes material inputs, transport of this material, and handling of waste water and solid waste (Dones et al., 2007). Similarly, the operation of the SCR unit retains NO_x-emissions and the process includes ammonia use, transport of ammonia and disposal of catalyst. Both oil inputs, SO_x retained and NO_x retained for the operation of the conversion units are modelled using values for the Ecoinvent process *hard coal burned in power plant* (Dones et al., 2007), although with some alterations for the retained SO_x. Nitrous oxide emissions arise from nitrogen in air used in the combustion process and from nitrogen in the fuel. It is assumed that nitrogen retaining materials for coal and wood combustion can be modelled similarly, and that differences in nitrogen contents in the two materials are balanced by lower combustion temperatures for wood combustion compared to coal combustion (Nussbaumer, 2003). Also oil inputs for power plant start-up is modelled the same for wood and coal combustion. Sulphur on the other hand needs to be scaled down for wood fuelled combustion compared to coal combustion, as there is a lower sulphur content in wood compared to hard coal; 98,4 % less in wood than coal (Skrifvars et al., 1997). There is no difference between the sulphur content in clean and waste wood (see below).

Emissions from combustion are modelled separately for the ten conversion options, with many similarities. The five conversion technologies (each with the option of clean or waste wood combustion) are assumed to have the same combustion technology, i.e. fluidised bed combustion, and no difference in emissions factors are therefore applied for these five technology options. On the other hand, differentiation between clean and waste wood is incorporated. Emission values for clean wood are found from several sources (see below), while emissions values for waste wood combustion are less available as waste is often co-combusted with other fuels (Tsupari et al., 2005). In addition, EEA (2009) reports no difference in emission factors for clean and waste wood for a fluid bed boiler. Based on this, waste wood emission values are calculated based on a comparison of the elementary analysis of clean and waste wood from an IEA produced database for biomass (n.d. b).

Air emission data is modelled from the following sources; measurements from Norske Skog's plant (CenBio, 2011), data from Nielsen et al. (2010) reporting emission data for wood combustion from decentralized CHP plants, and data from Tsupari et al. (2005) reporting technology, scale and fuel specific emissions. A combination of the mentioned sources are used; most emission factors will generally be lower for a 50 MW_{el} CHP compared to a CHP plant less than 25 MW_{el}, so the lower range of emissions from Nielsen et al. and CenBio are used, updating the N_2O and CH_4 values from Tsupari et al (2005). Condensate emissions are based on an IEA database (n.d. c). Emission data from all these sources, except for one (Tsupari et al., 2005), are representative for *clean* wood combustion. There are uncertainties in the emissions levels applied, but a combination of relevant sources limits these uncertainties. Air emissions from combustion will be discussed first, before the condensate emissions are discussed.

Air emissions from biomass combustion can be divided in two main groups: emissions from complete combustion and emissions from incomplete combustion (Loo and Koppejan, 2007). Emissions resulting from complete combustion are carbon dioxide (CO_2), nitrogen oxides (NO_x), nitrous oxide (N_2O), sulphur oxides (SO_x), hydrogen chloride (HCl), particulates and heavy metals. Minor and major combustion products caused by complete combustion are a result of properties of the combusted fuel. Potential differences between the ten conversion options will therefore be on clean and waste wood. Where emission data is not available on clean and waste wood, elementary analysis will be applied to calculate the emission factors.

CO_2-emissions originate from carbon in the fuel (Loo and Koppejan, 2007) and emission factors are calculated from equation 14, which states the CO_2 emissions per MJ energy at plant gate. The carbon content in wood is 51 wt.% (Loo and Koppejan, 2007; Skrifvars et al., 1997), and no difference between clean and waste wood is applied. Table 15 shows the operational CO_2-emissions for the five technology options. The direct CO_2 emissions from combustion are multiplied by a factor of 99 %, including the assumption that 99 % of the carbon in the fuel is converted to CO_2 emissions (U.S. Environmental Protection USEPA, 2010).

$$CO_2 - emissions = \frac{1}{LHV_{db}} * cc * \frac{44}{12} * \frac{1}{\eta} * 0{,}99 \qquad (14)$$

cc: carbon content
LHV_{db}*: lower heating value on a dry basis*
η*: efficiency*

[kg CO_2 / MJ useful]	**CHP, el**	**CHP, heat**	**Thermal, el**	**DH, heat**	**Boiler, steam**
Biogenic CO_2-emissions	320	160	240	112	108

Table 15: biogenic CO_2 emissions from biomass combustion for the different conversion technologies.

Nitrous oxide (NO_x) emissions are a sum of NO and NO_2 emissions, formed in three different ways: thermal NO_x, prompt NO_x and fuel NO_x (Nussbaumer, 2003). The first two are formed from nitrogen in the air at high temperatures, where prompt NO_x in the presence of hydrocarbons. These two sources of NO_x emissions are less important for biomass combustion because of relatively low temperatures. Fuel NO_x is formed from nitrogen in the fuel, and this is the main source of NO_x from biomass combustion. Emissions data for wood is used from available data on biomass combustion (Nielsen et al., 2010) and corresponds well with other sources (CenBio, 2011; EEA, 2009). The difference in nitrogen content between clean and waste wood is ten per cent (IEA, n.d. b), respectively 0,67 and 0,6 mass % on a dry basis, and this is also the difference in NO_x-emissions between clean and waste wood.

Nitrogen dioxide (N_2O) emissions result from complete oxidation of nitrogen in the combusted fuel, and generally N_2O-emissions are low from biomass combustion (Loo and Koppejan, 2007). Despite the relatively low emission values, N_2O is of high relevance because of its high global warming potential factor and an impact 23 times higher than that of CO_2 (Strømman, 2010). In this assessment, N_2O-emissions are modelled based on combustion technology, scale and fuel combusted – differentiating between clean and waste wood (Tsupari et al., 2005).

Sulphur oxide emission results from complete oxidation of sulphur in the fuel, and consists mainly of SO_2, but also of some SO_3, respectively about 95 % and 5 % of total SO_x. SO_2 is modelled from Norske Skog's plant (CenBio, 2011), and this value is slightly lower than what Nielsen et al. (2010) reports. No difference between clean and waste wood is used, as the sulphur content in average clean wood and average waste wood is the same – 0,1 mass % on a dry basis (IEA, n.d. b).

The chlorine content of biomass is low, 0,1 wt.% on a dry basis for both clean and waste wood (IEA, n.d. b), and part of this chlorine is released as hydrogen chloride to the atmosphere (Loo and Koppejan, 2007). Emission data for HCl is from Norske Skog's plant (CenBio, 2011), which also is the case for hydrogen fluoride (HF) emissions. No difference between clean and waste wood is applied.

Particulate emissions are relatively high from biomass combustion (Nussbaumer, 2003), and the particulates arising from complete combustion are from fly ash (Loo and Koppejan, 2007). Unburned hydrocarbon emissions resulting from incomplete combustion are discussed below. In this assessment the total particulate emissions are modelled from measurements at Norske Skog's plant (CenBio, 2011), and the total particulate emissions are split between particulate emissions larger than 10 µm (PM10) and particulate emissions smaller than 2,5 µm (PM2.5) ; respectively 54 % and 46 % (USEPA, 2011). No distinction between clean and waste wood is applied.

Heavy metals emissions are based mainly on measured data from Norske Skog's plant (CenBio, 2011), but also on literature (Nielsen et al., 2010). The applied emission values are overall slightly lower than what EEA (2009) reports for heavy metal emissions. All biomass contain heavy metals, which will either remain in the ash or evaporate (Loo and Koppejan, 2007), where the latter is of importance in this section. Distinction between clean and waste wood values is based on difference in average heavy metal contents (IEA, n.d. b), see Table 16. The heavy metal waste to clean fraction is multiplied by the emission factors used (CenBio, 2011; Nielsen et al., 2010), differentiating between clean and waste wood. For the heavy metals lacking data it is assumed that the waste wood value is the same as the clean wood value.

Heavy metal	Waste wood to clean wood fraction
Arsenic	1,3
Chromium	3,9
Copper	3,9
Manganese	0,6
Nickel	2,1
Lead	143,6
Vanadium	2,6
Zinc	33,3

Table 16: heave metal contents relevant for air emissions, expressed as waste wood to clean wood fractions (IEA, n.d. b).

Emissions resulting from incomplete combustion are carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC), polycyclic aromatic hydrocarbons (PAH), dioxins and particulates like unburned hydrocarbons (UHC) (Loo and Koppejan, 2007). These types of emissions are caused by operational characteristics like too low combustion temperature, too short residence time, lack of available oxygen or inadequate mixing of fuel and air. Optimizing these variables will reduce the stated emission categories.

First, carbon monoxide is converted to carbon dioxide if oxygen is available in the combustion process, and depends on the temperature – which makes CO emissions a good indicator of the quality of combustion (Loo and Koppejan, 2007). Large-scale biomass combustion normally has lower CO emissions than smaller units, as the combustion process can be optimized more easily, but CO can vary largely between different plants – even within plants of the same scale and technology (Tsupari et al., 2005). Fuels with, for instance, high moisture content may lead to high CO emissions. Due to these characteristics, using measured data from Norske Skog's plant (CenBio, 2011) gives the most realistic picture of carbon monoxide emissions, and this value is in line with, or slightly lower than data available in literature (EEA, 2009; Nielsen et al., 2010; Tsupari et al., 2005). No difference between clean and waste wood is applied to CO emissions (Tsupari et al., 2005).

Methane, CO and N_2O emissions often correlate (Tsupari et al., 2005). Large differences in emission values can be found, depending on fuel (e.g. moisture content and fuel size), combustion technology and earlier mentioned operating conditions. Technology, scale and fuel specific emission factors for methane is found from literature, differentiating between clean and waste wood (Tsupari et al., 2005).

Emissions of NMVOC have several of the same characteristics as CO and methane emissions; emissions result from too low combustion temperature, too short residence time or lack of oxygen (Loo and Koppejan, 2007). Emissions data for NMVOC is found in literature (Nielsen et al., 2010), and is in range with relevant data in literature (EEA, 2009; Tsupari et al., 2005). No difference between clean and waste wood is applied to NMVOC emissions.

Also polycyclic aromatic hydrocarbons (PAH) arise based on the same operational characteristics as CO and methane emissions (Loo and Koppejan, 2007), and are based on data from Nielsen et al. (2010). Naphthalene, which is a polycyclic aromatic hydrocarbon, is modelled separately based on the same source (Nielsen et al., 2010). Dioxin emissions also depend on combustion conditions and flue gas cooling, and the variation in emissions is high – even within the same plant. Dioxin emissions are modelled using data from Norske Skog's plant (CenBio, 2011), and is in line with other available data (Nielsen et al., 2010). There are not used any difference in PAH and dioxin emissions for clean and waste wood.

Particulates resulting from incomplete combustion are soot, char and tar (condensed heavy hydrocarbons), where soot mainly consists of carbon (Loo and Koppejan, 2007). Char particles have a low specific density and is to a high degree entrained in the flue gas. Unburned hydrocarbons (UHC) are modelled from Nielsen et al. (2010), with no distinction between clean and waste wood.

Finally, condensate emissions are based on values from IEA Bioenergy Task 32's database for condensate emissions (n.d. c). These values are for clean wood, and waste wood values are calculated based on the heavy metal fraction of waste to clean wood (IEA, n.d. b), see Table 17.

Heavy metal	Waste wood to clean wood fraction
Calcium	2,4
Magnesium	1,6
Potassium	0,6
Sodium	3,4
Zinc	33,3

Table 17: heavy metal contents relevant for condensate emissions, expressed as waste wood to clean wood fractions (IEA, n.d. b).

Continuing with wood ash; ash from combustion is assumed to be sent directly to sanitary landfilling, which is a common assumption for combustion of larger scale (Doka, 2009). The emission data for this process is updated from IEA's database (n.d. a) for ash, using data from several available species: wood, wood chips, sawdust, paper and waste wood. Average bottom ash values are used for all these species, finding the average emission data for clean wood and waste wood. The fraction of each emission to different compartments and assumptions regarding unspecified, low or high population density are assumed to be the same as for the emissions inventory in the Ecoinvent process *disposal, wood ash mixture, to sanitary landfilling* (Doka, 2009).

Table 18 shows the emission data used for clean and waste wood. Where no emissions data were available for waste wood, clean wood data is used; relevant for carbon dioxide, oxygen, chloride, manganese, cobalt, molybdenum, arsenic, cadmium, vanadium, barium and titanium. Waste wood has the highest emission factors for sulphur, aluminium, iron, copper, zinc, nickel and lead, while clean wood has the highest metal emissions for the remaining emissions (IEA, n.d. a).

[mg / kg$_{db}$]	**Clean wood**	**Waste wood**
Organic carbon	7,19E+03	5,00E+02
Carbon dioxide	4,63E+04	4,63E+04
Oxygen	1,03E+05	1,03E+05
Sulphur	4,34E+03	1,23E+04
Chloride	1,13E+02	1,13E+02
Silicon	2,33E+05	2,19E+05
Calcium	2,82E+05	2,47E+05
Magnesium	4,08E+04	3,41E+04
Potassium	5,43E+04	2,19E+04
Sodium	9,43E+03	1,02E+04
Phosphate	1,48E+04	1,24E+04
Aluminium	5,40E+04	1,14E+05
Iron	3,54E+04	5,32E+04
Manganese	1,56E+04	1,56E+04
Copper	1,06E+03	4,56E+03
Zinc	4,40E+02	1,72E+03
Cobalt	1,63E+01	1,63E+01
Molybdenum	3,33E+00	3,33E+00
Arsenic	4,83E+00	4,83E+00
Nickel	9,04E+01	1,30E+02
Chromium	8,00E+02	5,49E+02
Lead	8,21E+01	5,07E+02
Cadmium	2,03E+00	2,03E+00
Vanadium	3,31E+01	3,31E+01
Barium	7,97E+02	7,97E+02
Titanium	3,13E+02	3,13E+02

Table 18: ash emission data for clean and waste wood (IEA, n.d. a).

Finally, allocation is applied for the multi-output technology CHP, delivering electricity and heat. Energy allocation is used, which is both easy to use and often applied to CHP systems (Strömberg, 2002). The partitioning variables for heat and electricity are found from equation 10 and normalised to energy on a kWh basis. Based on the energy content of heat and electricity, each energy unit (kWh) is assigned the same load.

4.6 Energy distribution

The energy distribution step models the distribution of the produced energy from power plant to end user. Three different options are modelled; electricity, heat and steam distributed to end user. Included in the modelling are distribution infrastructure and losses, and also direct emissions to air for the electricity option. Figure 14 shows the flowchart for the energy distribution.

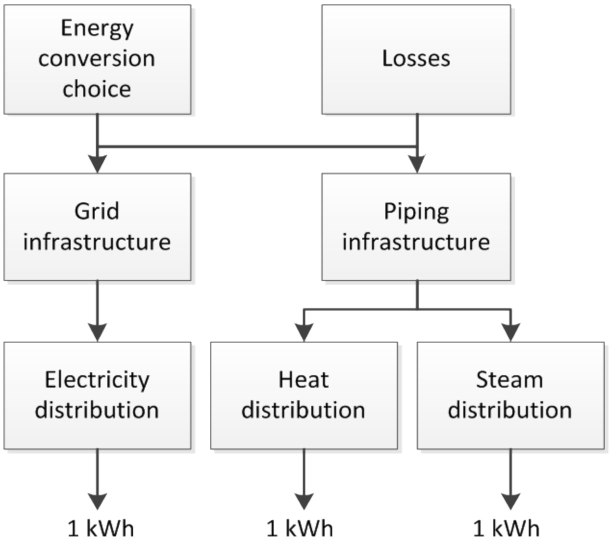

Figure 14: energy distribution flowchart.

The electricity distribution is modelled using the Ecoinvent process *electricity, high voltage, production NORDEL, at grid* (Dones et al., 2007), which includes electricity production, transmission network, losses and direct ozone and N_2O emissions to air. The transmissions losses are 13,3 %. To only model the electricity distribution, the produced electricity is subtracted from the process' inventory.

Heat and steam distribution is modelled using several different sources (Fröling and Holmgren, n.d.; Fröling et al., 2004; Fröling and Svanström, 2005; Guest et al., 2011; Persson et al., 2006). The district heat water piping infrastructure is modelled using three different sized piping networks, and the pipe distribution, total district heat production in 2009 and losses is the same as for Trondheim Energi. The steam distribution is modelled only with the smallest-sized diameter piping with no need for excavation and associated construction input. In addition, the steam distribution pipe length is assumed only to be 1/3 of the pipe length for water distribution. There are no direct emissions from the steam and waste distribution options. Losses are 12 % for water distribution, and assumed the same for steam distribution.

5 Scenario model

The six value chain steps described in the process LCI chapter can be put together to represent a set of possible value chains – a total of 80 possible combinations, taking into account that each of the feedstocks have three pre-treatment options except paper and cardboard waste, which can only be chipped and therefore only have one pre-treatment option. Each energy conversion choice has one energy distribution option, and P&C waste and wood waste implies waste wood emissions from the energy conversion step, while the rest of the feedstocks require the clean wood options. The waste wood TOP process applies to wood waste, while the clean wood TOP process applies for the remaining feedstocks. See Table 82 in appendix 8 for the list of feasible combinations.

All flow data is from 2010. Data are mainly based on official statistics from Statistics Norway, reporting forest harvest, waste flows, energy balance and industry energy use for 2010. Pellets data is obtained from the Norwegian Bioenergy Association's yearly market report for pellets and briquettes (NOBIO, 2010), while data on saw residues from Tellnes et al. (2011) maps the material flows for the Norwegian saw industry. The assessed data is also compared and partly built on the following two master theses:

- "*Logs, wood based products and pulp and paper products in Norway – product flows and value added in the wood based value chain*" by Rødland (2009) with data from 2006.
- "*Environmental assessment of scenarios for products and services based on forest resources in Norway*" by Grinde (2011) with data from 2006.

The assessed feedstocks, pre-treatment and energy conversion technologies together make up a market. This market consists of the feedstocks and technologies discussed above and this section aims at mapping the different flows. The result is a scenario model assessing the life cycle impacts of the modelled Norwegian bioenergy market. There are parts of the total Norwegian bioenergy market that are not assessed in this analysis; most importantly household consumption, but also a share of the total industry bioenergy use. In Norway, 47 % of the final bioenergy consumption in 2010 took place in households, while 28 % of the bioenergy was consumed by industries. Wood logs and pellets are the most important sources of bioenergy in households. Household consumption will not be discussed any further.

The Norwegian industries in 2010 purchased 12 % of the bio-based energy from the market, while the remaining 88 % was produced in the industrial production chain (SSB, 2011b). Out of the self-produced energy, 50 % comes from black liquor and 50 % from the industry's chips, bark and waste residues, where saw residues are the only feedstock of these assessed. This means that only saw residue combustion is assessed for energy produced by industries. Langerud et al. (2007) reports that 667 GWh of bioenergy used in industries comes from purchased wood waste from the market, and SSB reports the purchased biomass from market to be 617 GWh. Based on this it is assumed that all biomass purchased from the market for energy production comes from wood waste. Therefore, wood waste purchased to produce energy in industries and saw residues utilized for energy are the flows assessed related to energy – this accounts for about 14 % of the bioenergy used in industries.

5.1 Reference scenario

The material flows for the modelled system described above are tracked in the Norwegian economy, and the current Norwegian bioenergy system can be evaluated. In 2010, the Norwegian bioenergy consumption was 17,5 TWh (SSB, 2011a) – just below 22 % of the total energy consumption in Norway. This implies an almost 19 % increase in bioenergy use compared to 2009. Some parts of the Norwegian bioenergy system are excluded from this thesis; wood fuels used in residential heating and non-saw residue biomass used by industries. The total bioenergy consumption assessed in this work then equals 10,2 TWh. This section will describe this current Norwegian system, referred to as the reference scenario.

The feedstock flows represent the available resource pool for bioenergy production. The waste flows will be discussed first, before saw residues and forestry flows are discussed. The waste feedstocks are modelled using data from Statistics Norway (SSB) for 2010 (SSB, 2012b), see Table 19. Respectively 23 % and 59 % of all P&C

and wood waste is combusted for energy. The P&C waste flow is slightly lower than what Rødland (2009) and Grinde (2011) report, but this difference is small. For wood waste on the other hand, the material flow used in this assessment is higher than what Rødland (2009) and Grinde (2011) use. The reason for this is probably the waste export regulation from 2009 illegalizing export of organic waste (KLIF, 2008). Before this regulation, Norwegian organic waste was exported mainly to Sweden, and the regulation was meant to enhance the incentive to utilize these sorts of waste.

[1000 tones]	**Total**	**Energy utilisation**	
P&C waste	1107	254	23 %
Wood waste	1661	984	59 %

Table 19: Norwegian waste flows going to combustion for energy (2010) (SSB, 2012b).

The material flows for saw residues are modelled using data for the Norwegian sawmilling industry and main markets for 2010 reported by Tellnes et al. (2011). The industry residues are divided in two groups: residues sent directly to combustion and residues sent to the market. The residues sent directly to combustion have no pre-treatment, i.e. the saw residues direct pre-treatment option in this model, and the assumed energy conversion technology for this flow is steam production. The combusted residues are converted to steam utilised in the production process of sawn wood. The residues sent to the market are either used in the pulp and paper industry or used for pellet production (Langerud et al., 2007), where only the latter is of importance in this assessment, see Table 20.

[1000 tonnes]	**Total market**		**Relevant in this assessment**	
Total residues and shavings	409		52	
To combustion	11	*3 %*	11	*21 %*
To market	398	*97 %*	41	*79 %*

Table 20: saw residues in the Norwegian market (2010) (Tellnes et al., 2011).

Statistics Norway reports harvesting of forestry products divided between final harvest, thinning wood harvest and other harvest (SSB, 2012a), where *other* in this assessment is assumed to be harvest of forest residues. Both forest residues and thinning wood is assumed to go solely to combustion for energy, while final harvest is utilised by the wood processing industry in addition to households. Data on where final harvest goes is not available and final harvest, or stemwood, is therefore assumed to balance the feedstock supply to consumption. Assumed consumption is presented below.

	Volume fraction	**Total harvest [1000 tones]**	**Relevant in this assessment [1000 tones]**	
Final harvest	88 %	2244	374	41 %
Thinning wood	9 %	505	505	55 %
Forest residues	3 %	39	39	4 %

Table 21: Norwegian forestry flows (2010) (SSB, 2012a).

Four pre-treated materials are produced in this analysis; chips, pellet, TOP and saw residues direct (no further pre-treatment). Starting with the latter, the amount of saw residues analysed are the size of the saw residues to combustion flow, minus losses. There are at the moment no torrefaction units in operation in Norway, and the torrefied pellets flow is zero. There are some commercial scale plants under construction in Europe (ECF et al., 2010), but the import of TOP is assumed to be zero.

Data on pellets is found from the Norwegian Bioenergy Association (2010) reporting amount of pellets in the Norwegian market and amounts sold in units and bulks. The same assumption as Grinde (2011) is applied regarding the amount of pellets going to industrial combustion; the pellets sold in bulk are sent to industrial combustion, while the pellets sold in units are consumed in households. About 78 % of the pellets sold in the Norwegian market are produced in Norway, and of this about 2 % is exported (NOBIO, 2010). 24 % of the pellets in the market are imported. Table 22 shows the pellet flows in the Norwegian market for 2010. Grinde (2011) has in his thesis collected data on pellet production from 15 pellet producers in Norway and the wood input to production from his thesis is used also here; 0,4 % energy wood, 1 % wood waste and 98,6 % saw residues.

Pellets sale [1000 tones]		
Total	59	
Sold in units	19	33 %
Sold in bulk	40	68 %

Table 22: pellets sold in Norway (2010) (NOBIO, 2010).

Chip production is balanced to the amount of material needed for combustion in this analysis. Forest residues are solely going to chip production and the energy wood not going to pellet production is sent to chip production. Stemwood is also only being sent to chip production. Table 27 shows where each feedstock is being sent for pre-treatment.

Feedstock -> Pre-treatment [GWh]			
P&C waste	>>>	Chipping	1312
Wood waste	>>>	Chipping	5494
Wood waste	>>>	Pelletising	4
Wood waste	>>>	Torrefaction cw	0
Wood waste	>>>	Torrefaction ww	0
Stemwood	>>>	Chipping	1269
Stemwood	>>>	Pelletising	0
Stemwood	>>>	Torrefaction cw	0
Stemwood	>>>	Torrefaction ww	0
Forest residues	>>>	Chipping	140
Forest residues	>>>	Pelletising	0
Forest residues	>>>	Torrefaction cw	0
Forest residues	>>>	Torrefaction ww	0
Energy wood	>>>	Chipping	1795
Energy wood	>>>	Pelletising	1
Energy wood	>>>	Torrefaction cw	0
Energy wood	>>>	Torrefaction ww	0
Saw residues	>>>	Saw residues direct	48
Saw residues	>>>	Saw residues pelletising	191
Saw residues	>>>	Saw residues TOP	0

Table 23: feedstocks going to pre-treatment for the Norwegian reference scenario.

SSB reports the energy balance in Norway for different fuels (SSB, 2011a), see Table 24 for biomass. The energy converted post in this table is of importance in this assessment. The fraction of materials being converted in thermal power plants, CHP plants and district heating plants is used for all materials. This might not be the most accurate presentation, as waste materials are mainly utilised for heat production (Langerud et al., 2007). Even though, Statistics Norway's fraction between the conversion technologies is represented as an average for all bio-based materials (including waste) and therefore applied as described.

Norwegian energy balance 2010 [GWh]		
Production		17098
Import		444
Export		61
Gross domestic supply		**17482**
Energy converted		**4280**
In thermal power plants	*(8 %)*	353
In CHP plants	*(31 %)*	1325
In district heating plants	*(61 %)*	2603
Net domestic consumption		**13202**
Manufacturing, mining and quarrying		**4535**
Wood processing industries		3243
Manufacture of industrial chemicals		76
Manufacture of non-ferrous material		2
Other manufacturing industries		1215
Other sectors		**8667**
Agriculture		51
Private households		8277
Private and public services, incl. defence		291
Construction		47

Table 24: energy sources balance sheet for Norway 2010 (SSB, 2011a) [GWh].

5.2 Alternative scenario

An alternative scenario is developed to model a doubling of biomass for bioenergy compared to the 2007 level. As for the reference scenario, scenario values for feedstocks, treatment and energy conversion technologies are presented below. Generally, the resource with the highest potential for increased use is the forest resources; roundwood, forest residues and thinning wood (Trømborg, 2011). There is also a potential increase in use of by-products from industry and waste, though smaller.

As stated earlier in this thesis, the stem of the tree is the main goal of forestry today (Langerud et al., 2007). In a bioenergy perspective, the whole tree can be utilised – including crown, waste, branches, stumps and coarse roots. For Norway, and particularly the region in Eastern-Norway, there is a high potential for increased forest harvest, see Table 25. The gross and net sustained yield for stemwood harvest is given together with the average annual harvest between 1994 and 2003. The potential for increased harvest is the difference between the annual harvest and the net sustained yield, which is 3,6 TWh for Norway as a whole. The potential for forest residues is also indicated in Table 25, while stumps and roots are not included as this is outside the scope of this thesis. The total values for Norway are applied for the alternative scenario, as the case is representative for the country as a whole.

[TWh]	**Gross sustained yield**	**Net sustained yield**	**Average annual harvest**	**Economic potential FR**
Eastern-Norway	9.8	7.5	6.1	1.48
Total Norway	19.6	13.1	9.5	2.69

Table 25: stemwood and forest residues potential in Eastern-Norway and Norway total (Langerud et al., 2007).

Increased forest harvest can also result from non-conventional logging sites, like clearing from cultural landscape and under power lines (Langerud et al., 2007). There is scarce information regarding the level of extraction from such sites, but Langerud et al. (2007) suggests a potential of 0,5-1 TWh from clearing at cultural landscapes and 0,4-0,5 TWh under power lines. The harvest is a combination of whole-tree harvest, harvest of forest residues and to a small degree more mature tree harvest. It is assumed that the harvest can be modelled solely as thinning harvest, and that the total increase is 1,2 TWh.

Table 25 presents an *economic* potential. Both a theoretical potential and an economic potential exists for increased biomass harvest from forests (Langerud et al., 2007). The theoretical potential is greater than the economic potential, as a high share of the biomass is not available for energy purposes. The biomass might be too expensive to extract, it might be used in timber, paper or cellulose production, or it should be left in forest for environmental purposes. Generally, the level of cost is so high that only half of the annual growth is profitable to extract (KanEnergi, 2007). The growth in Norwegian forests is substantial, and the forests increase by 22-24 million m^3 per year. The extraction is only 8-10 million m^3 per year, and this leads to an increase in accumulated biomass.

Langerud et al. (2007) has calculated the availability of saw residues and reports a total volume of 2,85 million m^3 (excluding bark). This is slightly higher than the numbers reported by Tellnes (2011). Langerud et al. (2007) further reports that all residues from the sawmilling industry are utilised today, and there is no potential for further use. KanEnergi (2007) reports a potential of more than 4 TWh for saw residues, and it is assumed an increased use of saw residues of 2 TWh in the alternative scenario of this thesis. Waste resources will have a potential of increased use, particularly after 2020, as the level of construction and renovation is high. Langerud et al. (2007) suggests 1 TWh increased use of wood waste, but reports no values for paper waste. It is assumed that the paper flow going to combustion remains constant to the current level. Figure 5 shows that the paper waste flow has been rather constant the last 15 years, and a potential increase in this waste flow is assumed to be balanced by increased level of recycling. KanEnergi (2007) reports a potential 0,5 TWh for wood waste – only half of the value reported by Langerud et al. (2007). Values are also presented for forest fuels by KanEnergi (2007), and all values are presented for different cost levels. Generally, the values indicated by Langerud et al. (2007) are somewhat lower (except for waste wood). Table 26 shows the chosen values for both the reference and the alternative scenario.

Resource	Use today [TWh]	Increased use [TWh]	Total [TWh]
Stemwood	1,27	3,6	4,87
Energy wood	1,80	1,2	3,00
Forest residues	0,14	2,69	2,83
Saw residues	0,23	2,0	2,23
Wood waste	5,50	1,0	6,50
Paper waste	1,31	0	1,31
Total	**10,25**	**10,49**	**20,74**

Table 26: current bioenergy feedsctock use and potential increase towards 2020.

In addition to the values presented above, straw and grain residues have a potential increased use of about 2,5 TWh and biogas 1,1 TWh (Langerud et al., 2007). Adding this to the total increased use given in Table 26, a total potential of 14,1 TWh exists. On the other hand, the 14 TWh goal of increase is referred to 2008, and a total increase of 2,31 TWh took place from 2008 to 2010. This means that the values for increased use can tolerate some changes, as some of the bio-increase already has taken place from 2008 to 2010 as well as the fact that some feedstocks are not included. Either way, the alternative scenario modelled in this thesis is doubling the use of assessed biomass from 2010 to 2020.

Potential increased use of the different resources is presented above, and the treatment of these resources will now be discussed. Table 27 shows the pellet sale in Norway from 2004 to 2010, and the annual sale increase has been calculated. The average annual increase from 2004 to 2010 is 20 %, while the average annual increase the last five years is 26 %, excluding the decrease in production from 2004 to 2005. It is assumed that the pellet production will increase quite substantially from 2010 to 2020. As a base value it is assumed that the production will increase with 26 % every year in the alternative scenario. This adds up to a total increase of pellet production of about 260 % from 2010 to 2020. This number is used for the feedstocks utilised for pellet production in the reference scenario: waste wood, energy wood and saw residues. In addition, it is assumed an additional increase to account for a more aggressive bioenergy use towards 2020. This additional pellets increase accounts for *a share* of the increased use of stemwood, forest residues, energy wood and saw residues given in Table 25, subtracting the chips production (more below). For stemwood, forest residues and energy wood, the first two originally not utilised for pellet production, this share is one half, where the remaining half is utilised for TOP production (more below). For saw residues, this share is one third, an equal share going to TOP production and direct combustion of saw residues.

[tonnes]	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Pellet sale	22055	19497	30184	31868	39791	42943	58505
Increase	-2558	10687	1648	7923	3152	15562	-
Increase [%]	-11,6	54,8	5,6	24,9	7,9	36,2	-

Table 27: pellet sale in Norway from 2004 to 2010 (NOBIO, 2010).

For pre-treatment, it is further assumed that the chips production increases with 50 % towards 2020. The use of chips has an average, annual increase of 20 % from 2000 to 2010 (SSB, 2012a). The chips use the last ten years has experienced large fluctuations, and it is assumed that the chips production will decline as other pre-treatment options become more evident, e.g. the discussed increase in pellet production.

As stated above, there is also an increase in combustion of saw residues and TOP production. Direct combustion of saw residues will not be discussed any further, while TOP production should be discussed. Production of bio-coal, or torrefied wood, is one of the Norwegian Government’s measures to reduce the greenhouse gas emissions by 2020 (Regjeringen, 2011), and it is therefore in the alternative scenario foreseen a quite substantial increase of this pre-treatment option. Table 28 shows where each feedstock is sent to pre-treatment. Values (in GWh) are presented for both the reference scenario (2010) and alternative scenario (2020). All cases where the feedstock is going to chipping, the value has increased by 50 % (as discussed above), but for wood waste this is not the case. Wood waste going to pelletising is increasing with 260 %, and the remaining feedstock is not big enough to account for the 50 % increase in chips production. Therefore, a 260 % increase in pellet production from Wood waste is incorporated, and the remaining wood waste is sent to chipping.

Feedstock -> Pre-treatment [GWh]				
			2010	**2020**
P&C waste	>>>	Chipping	*1312*	1312
Wood waste	>>>	Chipping	*5494*	6485
Wood waste	>>>	Pelletising	*4*	13
Wood waste	>>>	Torrefaction cw	*0*	0
Wood waste	>>>	Torrefaction ww	*0*	0
Stemwood	>>>	Chipping	*1269*	1904
Stemwood	>>>	Pelletising	*0*	383
Stemwood	>>>	Torrefaction cw	*0*	383
Stemwood	>>>	Torrefaction ww	*0*	0
FR	>>>	Chipping	*140*	209
FR	>>>	Pelletising	*0*	1310
FR	>>>	Torrefaction cw	*0*	1310
FR	>>>	Torrefaction ww	*0*	0
Energy wood	>>>	Chipping	*1795*	2692
Energy wood	>>>	Pelletising	*1*	153
Energy wood	>>>	Torrefaction cw	*0*	150
Energy wood	>>>	Torrefaction ww	*0*	0
Saw residues	>>>	Saw residues direct	*48*	547
Saw residues	>>>	Saw residues pelletising	*191*	1185
Saw residues	>>>	Saw residues TOP	*0*	498

Table 28: biomass feedtocks going to pre-treatment (in GWh) for both the Norwegian reference scenario and alternative scenario.

The energy conversion choices might also be subject to a change in the future. The use of district heating is assumed to increase quite substantially (KanEnergi, 2007). Power production from biomass has been less profitable in Norway, but the introduction of electricity certificates in January 2012 (NVE, 2011) will very likely change this picture. The certificates are meant to increase the production of renewable energy, and the system, which is already in place in Sweden, leads to increased revenues for the power producer, financed by the consumers. Electricity production from biomass is suspected to dominate the tradable green certificate schemes in the Nordic countries (Unger and Ahlgren, 2005). Based on this expected increase in both power production and heat production, the increased use of biomass is assumed to be evenly distributed between the three different conversion technologies. The fractions presented for thermal power plants, CHP plants and district heating plants in Table 24 are therefore also applied in the alternative scenario.

6 RESULTS AND ANALYSIS

This chapter has two main parts. The first part will introduce the results from the process LCAs, while the second will present the results for the scenario LCAs. Four impact categories will be assessed for this study; global warming potential (GWP), terrestrial acidification potential (AP), particulate matter formation potential (PMFP) and freshwater ecotoxicity potential (ETP). The results are calculated using *Arda*, a graphical user interface in Matlab's runtime environment, together with two Matlab scripts, loading templates from Arda and performing LCA calculations respectively. See Table 51 and Table 52 in appendix 7 for scripts. Before presenting the results, the means of presenting them will be discussed.

There are a total of 80 value chains assessed in this thesis, see the complete list in Table 52 in appendix 8. The complete list of the value chains can be classified in different ways, for instance by feedstock, pre-treatment technology or energy service. For the process LCAs, the results will be classified by their conversion technology. The value chains also have a pattern of combusted material; the results for each energy conversion technology have the same sequence of combusted materials for the assessed impact categories. The results are assigned acronyms, representing the materials going to combustion for the different energy technologies. There are a total of 16 different materials going to combustion, where the acronyms below represent the combusted materials throughout the entire chapter:

- WC	Wood waste chips
- PC	P&C chips
- WP	Wood waste pellets
- WT	Wood waste TOP
- EC	Energy wood chips
- FrC	Forest residues chips

SC	Stemwood chips
EP	Energy wood pellets
FrP	Forest residues pellets
SP	Stemwood pellets
ET	Energy wood TOP
FrT	Forest residues TOP
ST	Stemwood TOP
SrD	Saw residues directly to combustion
SrP	Saw residues pellet
SrT	Saw residues TOP

The scenario LCAs are organised somewhat differently, presenting the results classified in three different ways: by feedstock, treatment and enduse. The material and technology options are of course the same for both the process LCAs and scenario LCAs, only the results are presented and classified differently. The scenario results will present both the material flows and bulk of each technology together with the GWP of each step. The reference scenario is discussed first, ending with the alternative scenario. The results in the alternative scenario will also be compared to the results of the reference scenario.

6.1 Process LCA

Four different impact categories are assessed in this thesis: global warming potential (GWP), terrestrial acidification potential (AP), particulate matter formation potential (PMFP) and freshwater ecotoxicity potential (FETP). Figure 15, Figure 18, Figure 19 and Figure 20 respectively present the results for the assessed impact categories. The results are categorised by energy conversion technology, with the purple representing the thermal energy plant option producing electricity, red representing the results for the district heating option, the blue being the boiler producing steam, and the green and turquoise representing the CHP option producing heat and electricity, respectively. Each unit step on the horizontal axis represents one of the combusted materials – 16 in total. Together with one of the five conversion technologies, this makes up the 80 different value chains assessed.

6.1.1 Global warming potential

The GWP for the assessed system will be presented in two different ways – excluding surface albedo effects and including surface albedo effects. The results which do not include albedo effects will be discussed first, and Figure 15 shows the GWP for the assessed system. The global warming potential ranges from 50 grams CO_2-equivalents per kWh to 514 grams CO_2-equivalents per kWh. The thermal power plant with electricity demand has a GWP ranging from 111-514 grams CO_2-equivalents per kWh, while the district heating plant has impacts ranging from 54-240 grams CO_2-equivalents per kWh. The CHP plant with heat demand shows a GWP between 52-231 grams CO_2-equivalents per kWh. The remaining two technologies show almost the exact same impact: 50-230 and 50-229 for the steam producing boiler and CHP plant with electricity demand, respectively. Each step of the different value chains will be discussed, starting with a further exploration of the energy technologies. A discussion of treatment, feedstocks and enduse will follow.

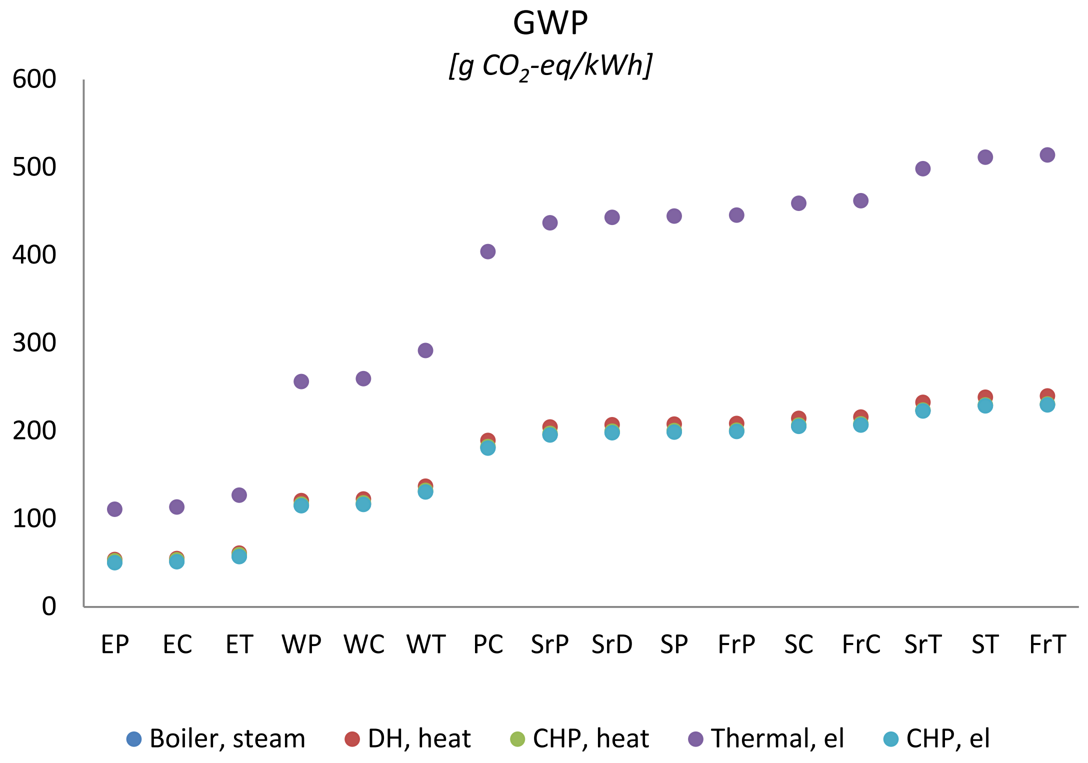

Figure 15: GWP [g CO_2-eq / kWh] for the different energy technologies and combusted materials (horizontal axis).

Starting with a look at the different energy conversion technologies in Figure 15, quite big differences are evident. The range in GWP for the five conversion options is already presented, and the thermal power plant option producing electricity has the highest impacts. The remaining technologies show quite similar impacts – the district heating option slightly higher than the remaining technologies. The CHP plant with electricity demand shows the lowest impacts, with the steam producing boiler nearly as low. The average difference between the CHP plant with electricity demand and the district heating plant is only about 5 %, relative to the district heating plant. The difference between the CHP plant with heat demand, the steam producing boiler and the CHP options are even smaller. The difference between the thermal power plant and district heating plant on the other hand is 53 %, relative to the thermal power plant. Comparing the two electricity producing units, the difference is 55 %, relative to the thermal power plant option. The reason for these differences is mainly based on the different conversion efficiencies for the different units, but is also affected by all the other steps in the value chains. For instance, the impacts of distribution choice affect the difference between the conversion technologies, which will become evident. This is particularly relevant for the CHP options with heat and electricity demand, with a relative difference of 1,5 %.

The impacts from the different conversion technologies in Figure 15 all show the same pattern. The impacts of each of the combusted materials show the same picture, where energy wood pellet (EP) is the value chain with the lowest impact and torrefied pellets from forest residues (FrT) has the highest impact for all conversion technologies. The three value chains with the lowest impacts all utilise energy wood as feedstock, while the three value chains with the highest GWP all produce torrefied pellets. Looking at pre-treatment choice, pelletising is always the most environmentally preferable option looking at GHG, while torrefied pellets are always the treatment option resulting in highest GWP. See value chain EP, WP, SrP, SP and FrP, with impacts ranging from 50-199 grams CO_2-equivalents per kWh for the CHP, electricity option and 111-446 grams CO_2-equivalents per kWh for the thermal, electricity option. For the TOP cases, see ET, WT, SrT, ST and FrT, with impacts ranging from 57-222 grams CO_2-equivalents per kWh for the CHP, electricity option and 127-497 grams CO_2-equivalents per kWh for the thermal, electricity option. The torrefaction process is the most advanced treatment option regarding operation and emissions, while chipping is the least advanced. Even though, chipping results in higher GWP than pellet production. See EC, WC, PC, SC and FrC, with impacts ranging from 51-206 grams CO_2-equivalents per kWh for the CHP, electricity option and 113-462 grams CO_2-equivalents per kWh for the thermal, electricity option. The reason for this result is the inclusion of storage losses and related emissions for the chipping alternative. The emission factors for chips storage are high, and N_2O and methane emissions are based on values given per day. Storage of chips therefore results in high, direct GHG emissions. While the chipping alternative assumes a storage time of six weeks, the chips storage time in the pellet and TOP cases is only two weeks prior to further treatment. In addition, storage of pellet and TOP indicates no storage losses, and therefore also no further emissions from storage.

Investigating the remaining treatment options, pelletising and integrated torrefaction and pelletising lead to lower impacts for the saw residue case – see value chain SrP and SrT in Figure 15. Chipping is not required in the saw residue cases and the storage emissions from chips storage are therefore also avoided. Also, the direct saw residue case has lower GWP than what is the case for stemwood and forest residues chipping. The energy wood and waste cases have lower GWP than the value chains just discussed, mainly based on the GWP_{bio} factors. Isolating the treatment options from the remaining value chain, treatment of saw residues is a more environmental friendly option, because both the storage emissions are lower and no chipping is required. The saw residue cases have GWP ranging from 198-222 grams CO_2-equivalents per kWh for the CHP, electricity option and 442-497 grams CO_2-equivalents per kWh for the thermal, electricity option, where the direct case has the lowest impacts and TOP the highest. Looking at the treatment technologies, pelletising has the lowest GWP, with chipping and integrated torrefaction and pelletising following. Generally, the relative difference between TOP and pelletising is 13 %, while the relative difference between chipping and pelletising is only 2 %.

The feedstocks in the different value chains will now be discussed. Energy wood has already been stated to have the lowest impact overall. The GWP from the energy wood value chains is on average 53 grams CO_2-equivalents per kWh for the CHP, electricity option and 117 grams CO_2-equivalents per kWh for the thermal, electricity option – see value chain EP, EC and ET. The main reason for the low results is the low GWP_{bio} factor for thinning wood. This factor determines the biogenic CO_2 emissions throughout the entire value chain - and therefore, has a huge impact on the results. The wood waste feedstocks are second in line regarding preferable feedstocks – see value chain WP, WC and WT in Figure 15. The P&C waste is next in line, with higher impacts than wood waste mainly because of both lower density and heating value (see Table 7). The average GWP for the value chains including wood waste and P&C waste is 120 and 181 grams CO_2-equivalents per kWh for the CHP, electricity option respectively, and 269 and 404 grams CO_2-equivalents per kWh for the thermal, electricity option respectively.

The remaining nine value chains utilise the remaining three feedstocks; stemwood, forest residues and saw residues. The three feedstocks have the same assumed GWP_{bio} factor, so the differences are therefore smaller. Forest residues show the highest GWP - see value chain FrP, FrC and FrT, with an average GWP of 212 grams CO_2-equivalents per kWh for the CHP, electricity option and 474 grams CO_2-equivalents per kWh for the thermal, electricity option. The baling process is responsible for a quite high share of the feedstock GWP for forest residues. The main reason for this is the plastic used to wrap the bales – responsible for more than 30 % of the emissions from the baling process. The CO_2 emissions from dry-matter losses are responsible for only a small share of the GWP from the baling process. Stemwood is the feedstock with the second highest GWP, see value chain SP, SC and ST, with an average GWP of 211 grams CO_2-equivalents per kWh for the CHP, electricity option and 474 grams CO_2-equivalents per kWh for the thermal, electricity option. Forest residues are a by-product from stemwood harvest and mass allocation between the two is applied. The reason for forest residues ending up with a higher GWP than stemwood is the included bundling process taking place before forwarding to landing, as well as both lower density and heating value for forest residues compared to stemwood. Bundling eases the handling and transport as the density increases slightly, but shows high impacts. The saw residues cases are already discussed together with treatment option, and overall saw residues have lower GWP than what is the case for stemwood and forest residues.

Finally, the results in Figure 15 will be discussed based on the distribution method. Each conversion choice has only one distribution method, i.e. heat, steam or electricity. The average GWP in Figure 15 categorised by enduse gives 162 grams CO_2-equivalents per kWh for steam, 166 grams CO_2-equivalents per kWh for heat, and finally 261 grams CO_2-equivalents per kWh for electricity. The results are strongly affected by the other value chain steps, in particular energy conversion. In fact, when isolating the distribution results from the remaining steps, the picture is quite different, see Figure 16. Electricity is actually the distribution choice with the lowest GWP, contributing to the main difference in GWP between the CHP plant option delivering heat or electricity. Electricity distribution only has 4 % of the impacts of heat distribution, while steam distribution has 5 % of the impact of heat. Heat distribution has a GWP of 47 CO_2-equivalents per kWh, while electricity and steam have a GWP of 2,0 and 2,1 CO_2-equivalents per kWh respectively. The main reason for the high impacts of heat distribution is the length of the heat distribution network compared to steam, and also the excavation needs. The asphalt inputs have particularly high impacts for heat distribution.

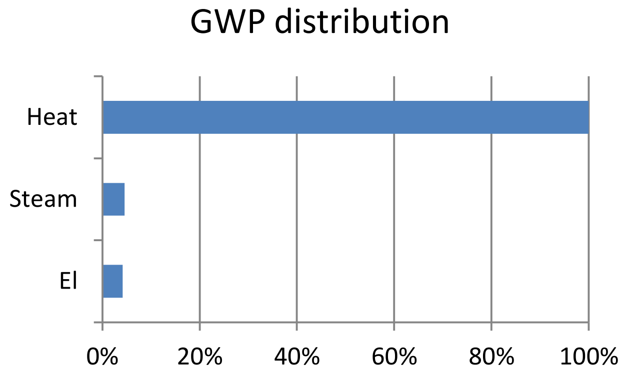

Figure 16: the GWP from the three distribution options heat, steam and electricity.

The difference between the value chain with the highest impact, i.e. forest residues TOP combusted in a thermal power plant producing electricity, and the lowest i.e. energy wood pellets combusted in a CHP plant demanding electricity, is huge. This difference is 90 %, reduced to 78 % comparing forest residues TOP and energy wood pellets combusted in the same conversion unit. The average GWP presented for the different feedstocks show a difference of 55 % between the results utilising the thermal power plant technology and the CHP, electricity technology.

Comparing the share of fossil CO_2 emissions to total GWP, an average value of 3 % is found. The fossil GWP share is slightly higher for the heat producing cases; about 4 %, and lower for the electricity producing cases; about 2 %. The forest resources generally have a higher share of fossil GWP than the remaining value chains. Particularly energy wood has high shares. The reason for this is harvesting and forwarding to forest road, both of which are diesel intensive processes. Stemwood and forest residues have a lower share of fossil GWP because harvest is commercialised today, i.e. economy of scale. Forest residues have a higher share of fossil GWP than stemwood because of baling. Forest residues have a smaller mass allocation factor, implying less impact from harvest, but this is outweighed by the GWP intensive baling process. The lowest fossil CO_2 value can be found for the waste feedstocks.

Finally, the results for GWP including surface albedo effects will be investigated. Figure 17 shows the results corrected for albedo effects. The surface albedo effects are calculated from albedo assumptions presented in page 19. The picture in Figure 17 is quite different to Figure 15. Energy wood is still the most environmentally preferable option, and integrated torrefaction and pelletising is the least preferable treatment option for all feedstocks. The GWP is ranging from 50-411 grams CO_2-equivalents per kWh, i.e. decreasing from 50-514 grams CO_2-equivalents per kWh when surface albedo effects are not included. The difference between the conversion technologies is still clear, with impacts ranging from 111-410 grams CO_2-equivalents per kWh for the thermal, electricity option, and 50-183 grams CO_2-equivalents per kWh for the CHP option with electricity demand. The steam producing boiler has a GWP ranging from 50-184 grams CO_2-equivalents per kWh, while the district heating option and CHP option with heat demand have impacts ranging from 54-191 and 52-184 grams CO_2-equivalents per kWh respectively. This means that the relative difference between the thermal, electricity unit and district heating unit is still 53 %, and the difference between the district heating option and CHP option with electricity demand is still about 5 %.

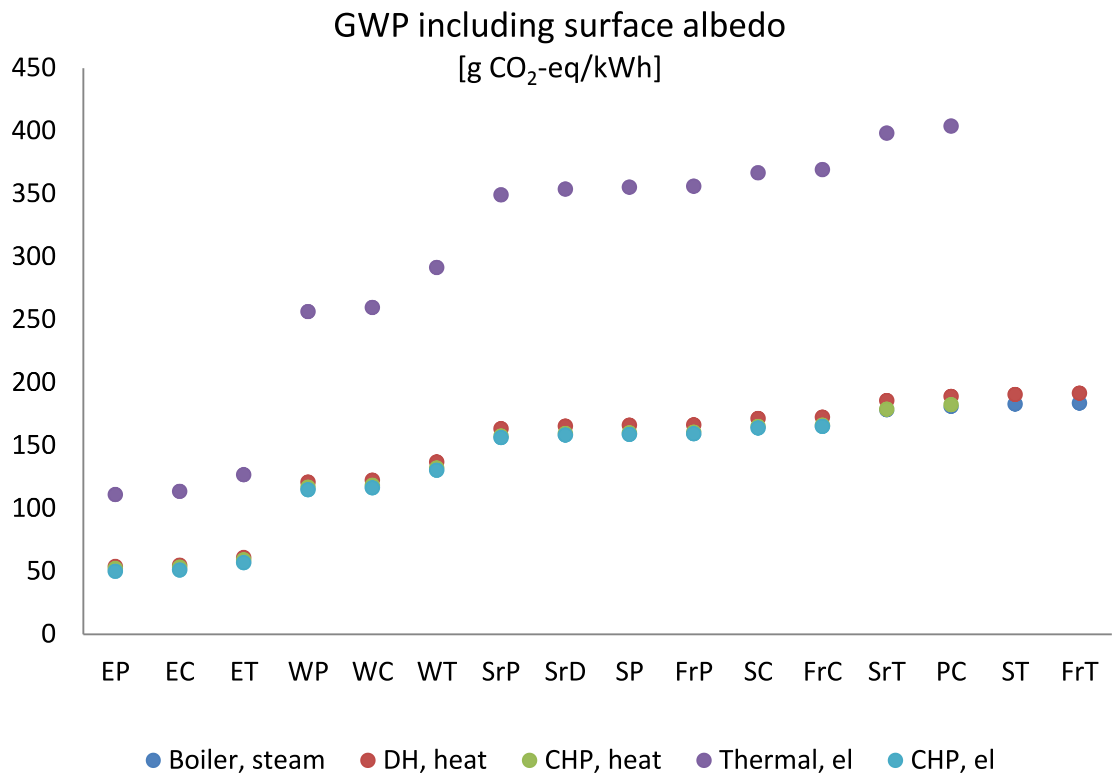

Figure 17: GWP [g CO_2-eq / kWh] for the different energy technologies and combusted materials (horizontal axis) including surface albedo effects.

The factor shifting the results in Figure 17 compared to Figure 15 is the albedo effect for the forest resources cases. Both energy wood and waste wood still have the lowest GWP, even though albedo effects are not included for these feedstocks. The GWP for the forest resource cases with included albedo effects are 20 % lower compared to the results for the same resources in Figure 15. The included albedo effects cause a much more favourable forestry system than what is the case excluding albedo effects. The results for waste resources and energy wood in Figure 17 are the same as the results given in Figure 15.

Looking at pre-treatment, the results are the same as found when excluding albedo effects. Pelletising is the preferred treatment options looking at GWP, while integrated torrefaction and pelletising is the least preferable. The differences between treatment options are small though. Figure 17 shows that the most important value chain options are feedstock and energy conversion technology. The value chains with the highest impacts utilise saw residues as feedstock. The preferred feedstock not including forest resources is wood waste.

6.1.2 Acidification potential

Looking at acidification potential for the different value chains, a somewhat similar picture takes place as in Figure 15 regarding energy conversion technologies. Figure 18 shows the AP for all the value chains, structured in the same way as for the GWP. As for GWP, the thermal power plant has the highest impact also for AP, ranging from $8,9*10^{-4}$ to $1,3*10^{-3}$ kg SO_2-equivalents per kWh. The district heating option, together with CHP with heat demand, follows, while the steam producing boiler and CHP plant with electricity demand have the lowest AP. The electricity demanding CHP plant has an AP ranging from $4,0*10^{-4}$ to $5,8*10^{-4}$ kg SO_2-equivalents per kWh. The difference between the thermal power plant and the CHP plant with electricity demand is 55 %. The difference between the value chain with highest and lowest impact for GWP (FrT in thermal, el and PC in CHP, electricity) is 68 %, reduced to 30 % for the value chains with the highest and lowest impact within the same conversion technology.

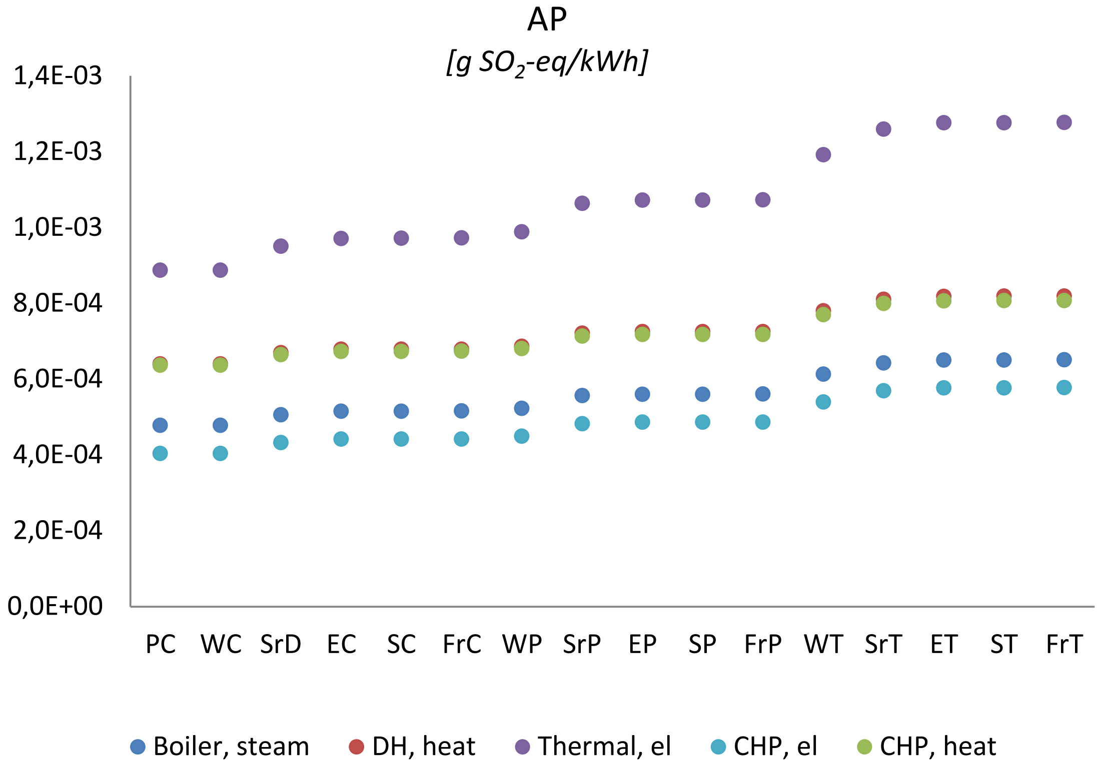

Figure 18: AP [kg SO_2-eq / kWh] for the different energy technologies and combusted materials (horizontal axis).

For acidification potential, the chipping value chains come out as the best options, with five out of the six values with the lowest impacts utilising chipping as pre-treatment option for each conversion choice. The sixth value chain utilises the direct saw residues treatment option. The waste resources come out as the best feedstock option, with saw residues following. Looking at the forest resources, the sequence is the same as for GWP; energy wood is the most preferable while forest residues the least. Integrated torrefaction and pelletising is the worst treatment option regarding AP, where all the five value chains within each conversion option utilise this treatment choice. A small jump is actually visible for the five last value chains, which are the TOP value chains. All the value chains in between the chipping and TOP value chains utilise pelletising as treatment option. For acidification potential, the pre-treatment choice affects the results to a higher degree than what is the case for feedstocks.

6.1.3 Particulate matter formation

Figure 19 shows the particulate matter formation potential for the different value chains. As for the other two impact categories, the results are categorised by conversion technology. The picture is quite different from the other two impact categories assessed. The differences are greater between the conversion technologies, but smaller for the different materials combusted. The thermal power plant has no longer the highest impact. The heating units, i.e. the district heating plant and the CHP plant with heat demand, have the highest impacts, while the CHP plant with electricity demand has the lowest impacts. The difference between the two CHP units is 88 % on average, relative to the heating unit. The difference between the value chain with the highest impact and the value chain with the lowest impact is 94 % overall, relative to the value chain with the highest impact. Investigating the difference between the value chain with highest and lowest impact within the same conversion unit, the difference is 60 % on average for the electricity units and only 8 % for the heating units. The relative difference between the highest and lowest impacts for the steam unit is in between the two values presented. The value chain with the lowest impact is saw residues directly combusted in the CHP plant with electricity demand and the value chain with the highest impact is forest residue pellet combusted in the district heating plant.

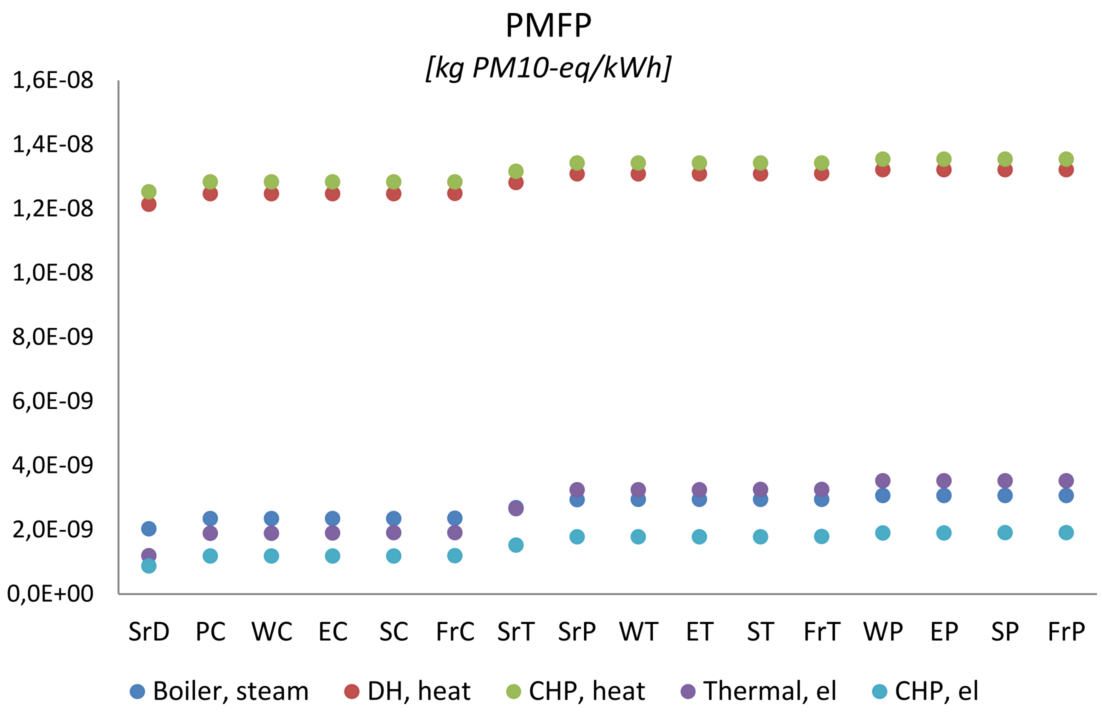

Figure 19: PMFP [kg PM_{10}-eq / kWh] for the different energy technologies and combusted materials (horizontal axis).

The large difference between the heat producing units and the electricity producing units points to the importance of distribution choice regarding particulate matter formation potential. Inputs of toluene and polyethylene and diesel use in the heat distribution step cause a high PMFP, as it results in high particulates, SO_x and NO_x emissions. Looking at feestocks, the saw residues cases are the most advantageous, with the waste resources following. As before, energy wood is the preferred forest resource while forest residues the least preferable. As has been stated earlier, baling of forest residues contributes to the impacts. Looking further at pre-treatment choice, the chipping options show low impacts. The four value chains with the highest PMFP all have the pre-treatment option of pelletising. Integrated torrefaction have impacts in between chipping and torrefaction. All waste resources and saw residues value chains have lower impacts than all torrefied and pelletised forest resources. The electricity use is important for PMFP, and the Nordic electricity mix is utilised throughout the assessment. Chipping has lower electricity inputs than the remaining treatment options.

6.1.4 Freshwater ecotoxicity potential

Figure 20 shows the freshwater ecotoxicity potential for the assessed system. The results show clear differences between the energy conversion units, with the heat producing units showing the highest impacts. As has been the case for all impact categories assessed, the CHP plant with electricity demand has the lowest impacts. The FETP ranges from 2,8*10^{-}3 to 3,6*10^{-2} kg 1,4-DCB-equivalents per kWh. The value chain with the lowest impact is the direct saw residues case combusted in the CHP plant with electricity demand, while the value chain with the highest impact is pelletised forest residues combusted in the CHP plant with heat demand. The relative difference is 87 %, reduced to 57 and 8 % comparing the value chain with highest and lowest impact within the electricity and heat conversion units respectively. The difference for the stem unit is 24 %.

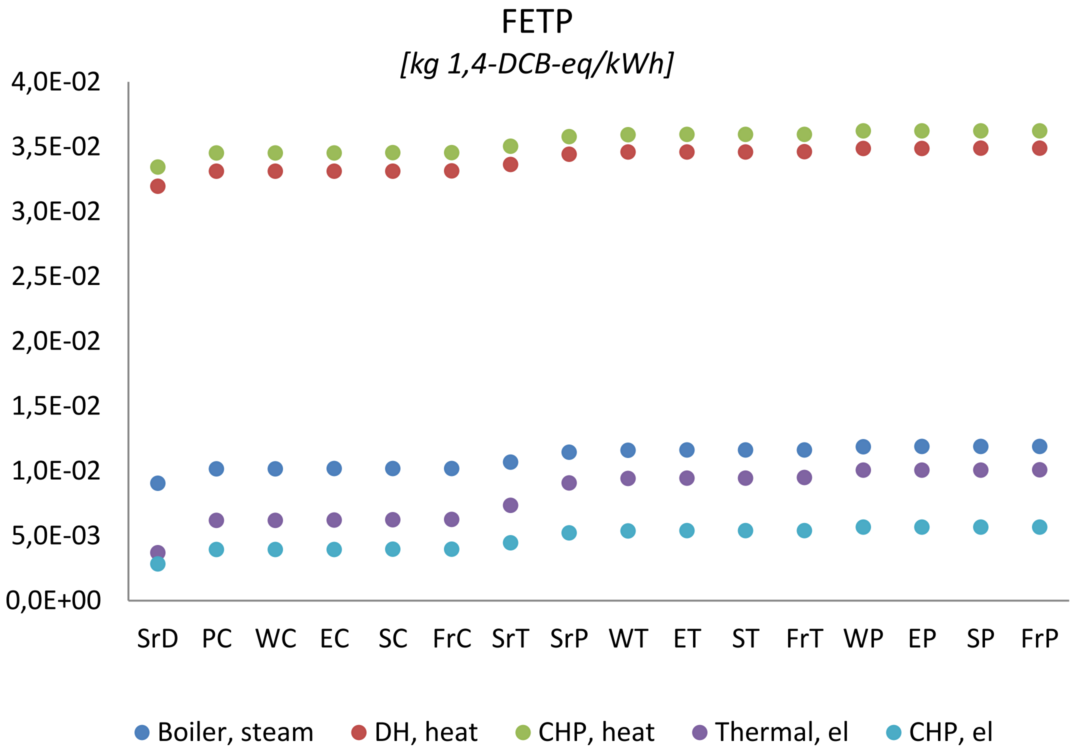

Figure 20: FETP [kg 1,4-DCB-eq. / kWh] for the different energy conversion technologies and combusted materials (horizontal axis).

The FETP picture is very similar to PMFP. As was the case for PMFP, chipping is the preferred treatment option, and pelletising the least preferred. In fact, the sequence of combusted materials and related impact is the same for FETP as for PMFP. This sequence will therefore not be discussed any further. The low impacts of saw residues and waste resources point to the benefit of utilising used biomass as raw material. Extraction and harvesting of forest resources are more impact intensive than collection of used wood type.

6.1.5 Individual value chains

Some of the value chains analysed are of greater relevance than others; some because they represent today's situation and some because they are assumed to be of importance for the future system. Four value chains will be investigated beyond the results presented above. These are the value chains thought to be of considerable importance today, or will be in the future. Together these four value chains represent important parts of the total system, and include a TOP value chain, a sawmilling residue case, a waste case and a value chain utilising forest residues. As stated earlier in this study, torrefaction is foreseen as an important treatment option by the Norwegian Government, and the saw residues and waste are representing the bio-share originating from the wood processing industry and waste flows in Norway. To complete the picture, a forest resource feedstock is included in accordance with the potential of increased forest harvest.

The TOP value chain chosen utilises the stemwood feedstock. The saw residue case is assumed to go to pellet production, as the bulk of this feedstock is utilised in this treatment technology. Finally, both the waste case and forest residue case are assumed to be chipped before combustion. The waste case assumed is the wood waste feedstock, which is assumed combusted in a district heating plant. Also the saw residue pellet is assumed combusted in a district heating plant. Today, waste is mainly combusted in district heating plants, and this is also the case for industrial combustion of pellets. The TOP value chain and the forest resource alternative are assumed to be converted in a CHP plant utilising electricity. The forest resource case assumed is forest residues, which have a great potential beyond today's use. Forest resources generally have a great potential, and can be used to produce electricity from biomass. The value chains chosen then cover a range of feedstocks, treatment options and the two most important enduse services. CHP with electricity demand and district heating are stated to not have too high a difference – which is the case for the thermal power plant producing electricity for instance. This allows for a fair comparison. The systems will be compared across the same range of impact categories that is presented above. The results will be presented for the waste case first, with the saw residue case, forest resources case and torrefaction case following.

Figure 21 shows the impact for chipped waste combusted in a district heating plant. The figure shows a breakdown between the different steps, i.e. feedstock, pre-treatment, conversion, energy distribution and transport. The case has a total GWP of 122 grams CO_2-equivalents per kWh. The bulk of the GWP takes place at energy conversion, amounting to 96 % of the total GWP. The impacts from feedstock production and transportation are negligible in comparison. Enduse accounts for 2 % of the total emissions. For comparison, the GWP from chipped waste combusted in a CHP plant with electricity demand is 116 grams CO_2-equivalents per kWh – slightly lower because of lower GWP from enduse. Investigating the remaining three impact categories the importance of the enduse and transportation steps increases. For AP, conversion accounts for 59 % of the total impacts, enduse for 33 %, and transportation for 6 %. Looking at the absolute value for AP, the value is 7 % higher than the average for combusted materials in district heating units. For PMFP and FETP, the conversion step's share of total impacts has decreased to 7 and 9 % respectively, while enduse accounts for 85 and 83 % respectively. As before, inputs of toluene and polyethylene cause high PMFP impacts from heat distribution. Also diesel use from e.g. excavation results in high impacts. For FETP, metal disposal from heat distribution infrastructure is responsible for high impacts. Treatment is responsible for 23% of the impacts for FETP, and 2 % for PMFP and AP.

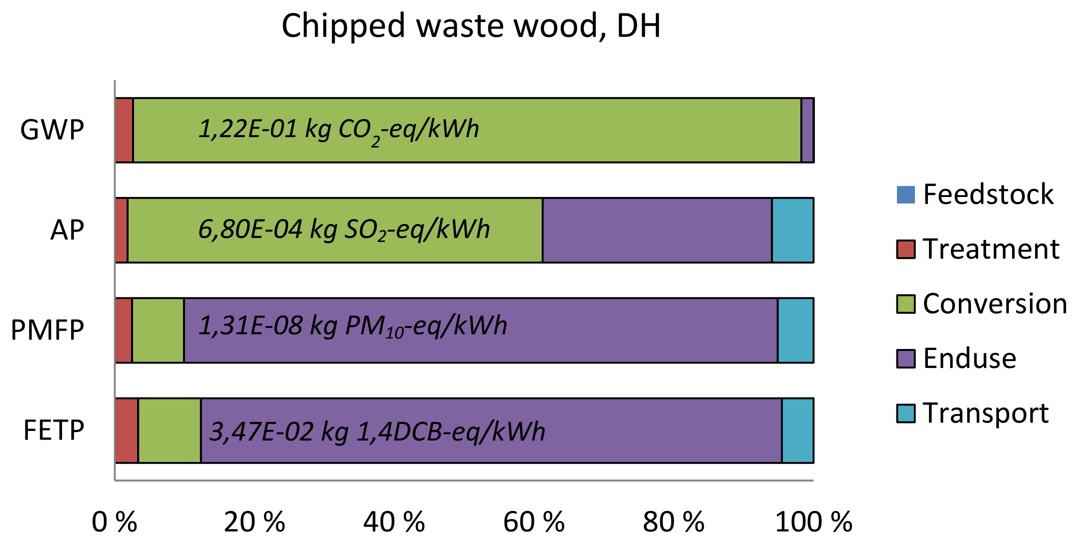

Figure 21: life cycle impacts for chipped waste wood combusted in a district heating plant. Total impacts per functional unit are indicated for the four impact categories, disaggregated between the five value chain steps.

Figure 22 shows the impacts for saw residues pellet, also combusted in a district heating plant. The GWP is 163 grams CO_2-equivalents per kWh – 25 % higher than chipped waste combusted in the same unit. The conversion step is of even higher importance for saw residues pellet, accounting for 98 % of the total GWP. The main reason for a higher GWP is the higher GWP_{bio} factor, where also the bulk of the biogenic CO_2 emissions are emitted from the conversion step. Enduse is the biggest contributor to the remaining GWP. For the remaining impact categories, treatment is responsible for 2 % of the total impact. For AP, energy conversion accounts for 61 % of the total impact, where the total AP is 4 % lower than the average AP for the 16 combusted materials assessed for district heating. Enduse has a share of 31 % of the total AP, while transport is responsible for 6 %. Moving on to PMFP and FETP, conversion is responsible for 7 and 9 % of the total impact in the respective categories. Enduse accounts for 85 and 84 % of the total impacts for PMFP and FETP respectively, while transport is responsible for 6 and 5 %. Comparing the total values to the average values for combusted materials in district heating plants, saw residues pellets have impacts 1 % below the average for AP, and 2 and 1 % above for PMFP and FETP respectively.

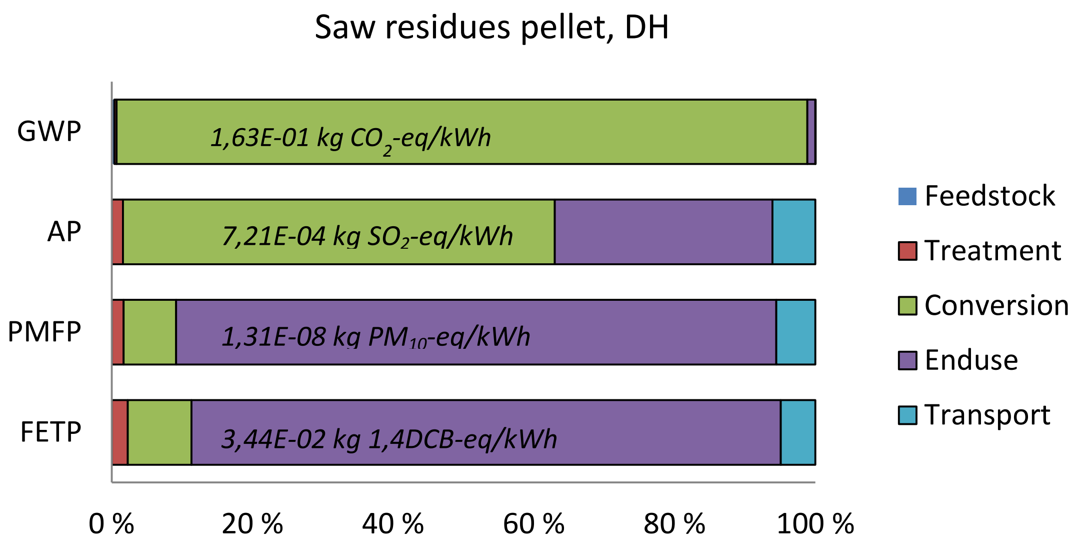

Figure 22: life cycle impacts for saw residues pellet combusted in a district heaing plant. Total impacts per functional unit are given for the four impact categories, disaggregated between the five value chain steps.

Moving on to forest residues chipped and combusted in a CHP plant with electricity demand, Figure 23 shows the impacts. The total GWP is 165 grams CO_2-equivalents per kWh. Also for chipped forest residues, conversion accounts for the bulk of the impacts with 94 % of the total GWP. The feedstock step accounts for 4 % of the total GWP, while treatment is responsible for 2 %. Compared to the two cases already discussed above, the feedstock step is now responsible for a higher share of the total GWP. This is mainly based on the included baling process, which causes quite high climate change potential. The share of fossil CO_2 emissions is also quite high for this value chain – 16 % of the total GWP. The GWP from forest residues cases were stated to have quite high impacts when not including surface albedo effects, but this picture changes when including such effects. For the remaining impact categories, the feedstock step causes fewer impacts, contributing to 1 % of the total impact for both PMFP and FETP. The energy distribution step causes 2 and 3 % of the total impacts for PMFP and FETP respectively. Energy conversion is responsible for the bulk of the impacts for AP, PMFP and FETP with 97, 70 and 67 % of the total impacts respectively. Transport is less important than the previous cases, causes negligible impacts for the four impact categories assessed. The treatment step is causing quite high impacts for PMFP and FETP, with 27 and 28 % of the total impacts respectively. For GWP and AP the treatment step is responsible for 2 and 3 % of the total impacts.

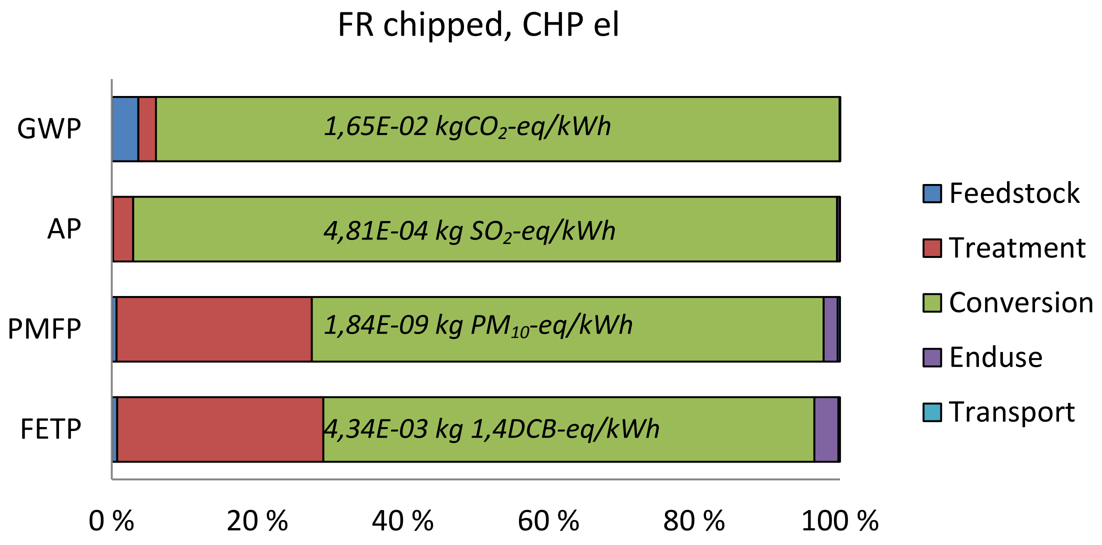

Figure 23: life cycle impacts for forest residues chipped and combusted in a CHP plant with electricity demand. Total impacts per functional unit are given for the four impact categories, disaggregated between the five value chain steps.

Finally, the results for the stemwood TOP case is presented in Figure 24. The value chain has a total GWP of 182 grams CO_2-eq per kWh (including albedo effects). Conversion is still the step contributing the most to the total GWP with a share of 85 % of the total impacts, but pre-treatment has an increased importance with 13 % of the total GWP. The feedstock step is responsible for 2 % of the total impacts. Overall, treatment is of higher importance to the overall impacts, and the value chain step is responsible for 20, 20 and 23 % of the total impacts for AP, PMFP and FETP respectively. Transport accounts for 6, 32 and 25 % of the total impacts respectively for AP, PMFP and FETP, while enduse only is responsible for 1 and 2 % for PMFP and FETP. As before, conversion is the main contributor to all impact categories, responsible for 74, 47 and 50 % of the total impact for AP, PMFP and FETP. Comparing stemwood TOP to the other value chains combusted in a CHP plant with electricity demand, the impacts are higher for both AP, PMFP and FETP, wiht 16, 13 and 11 %, repectively, compared to the average. The GWP from the stemwood TOP value chain compared to the other value chains combusted in a CHP plant with electricity demand is substantially lower. The reason for this is the inclusion of surface albedo effects.

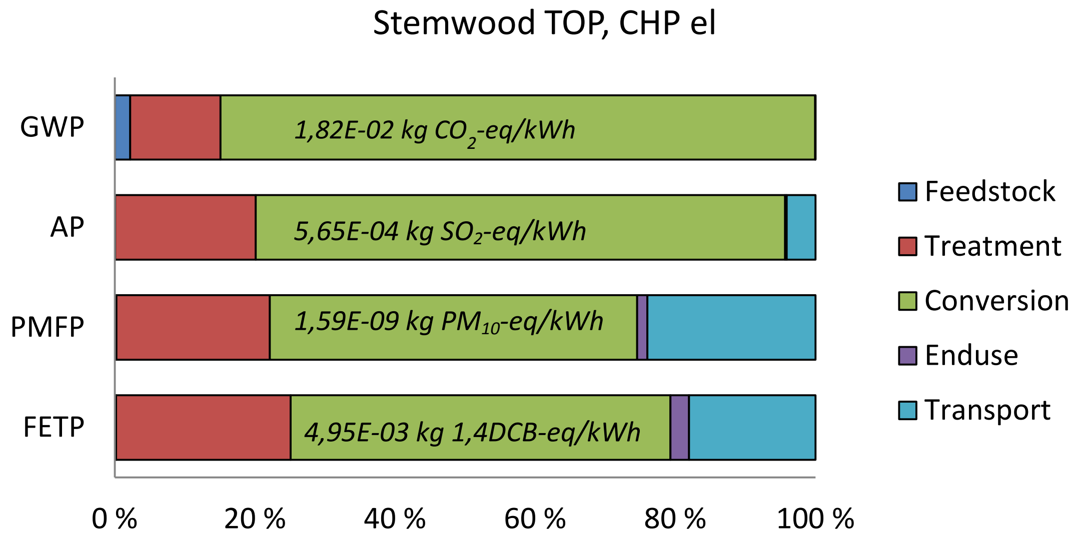

Figure 24: life cycle impacts for stemwood TOP combusted in a CHP plant with electricity demand. The total impacts are indicated for the four impact categories assessed, disaggregated between the five value chain steps.

Comparing the four value chains assessed individually to each other, the chipped waste wood case comes out as the best for GWP. The saw residues pellet case has the second lowest impacts. The stemwood TOP case has the highest GWP, 39 % higher than the waste wood case. The main reason for this difference is handling of biogenic CO_2 emissions. Saw residues, forest residues and stemwood are assigned the same GWP_{bio} factor, and all these cases have surface alebdo effects included. The albedo effects reduce the overall GWP for the forest residues cases by 20 %. The chipped forest residues case comes out as the best option for both AP and FETP, while the saw residues case comes out as the worst option for AP. The stemwood TOP case has 9 % higher GWP than the forest residues case, and comes out as the best option for PMFP. The PMFP from both chipped waste wood and saw residues pellets is substantially higher than both torrefied stemwood and chipped forest residues. Overall, the CHP option with electricity demand has lowest impacts for all impact categories. Comparing the four cases assessed individually, the waste wood case is performing best for GWP, but the the two electricity producing options perform considerably better for the three remaining impact categories assessed.

6.2 Scenario LCA

This part will present the results for the scenario LCAs. The material flows will be presented first, comparing the reference and alternative scenarios. Results will then be presented for climate change impact (in CO_2-equivalents). Feedstock, pre-treatment and distribution choices are analysed, where the conversion technology remains constant for the reference and alternative scenario. The focus is therefore on the produced energy service rather than the technology for conversion. Transport should not be forgotten, but will not be discussed any further in this part. All impacts presented are for the entire value chains, but are categorised in different manners, i.e. by feedstock, treatment or energy service. This is done to show the impact pattern of the Norwegian bioenergy market. The results presented include albedo effects for the three cases where such effects are considered, i.e. for stemwood, forest residues and saw residues.

6.2.1 Energy flows

The reference scenario presents the current, Norwegian system assessed. All data is from 2010, and will be referred to as the current reference system. The alternative scenario represents a 14 TWh increase in bioenergy use in Norway towards 2020. Starting with the feedstocks, Figure 25 presents the feedstock flows for the reference and alternative scenario respectively. The predominant flow in Norway today is wood waste. This waste material accounts for 54 % of the total feedstocks in the system assessed. The second biggest feedstock is the forest resource energy wood. Paper and cardboard waste follows, accounting for 13 % of the assessed feedstock market. The amount of stemwood going to bioenergy is almost as high; 12 %. Forest residues have the smallest share in the current system, with only 1 % of the market. Saw residues are only slightly higher, accounting for 2 % of the total feedstocks assessed. Investigating the projected feedstock flows towards 2020, wood waste is still the most important and dominates 31 % of the market. Both waste flows have decreased compared to the reference scenario though and P&C waste only accounts for 6 % of the total feedstock flows in the alternative scenario. Stemwood have experienced a doubling in market share, and accounts for 24 % of the feedstock market in 2020. Forest residues have the highest increase, and dominate 14 % of the market. Saw residues have also experienced a high increase, from 2 % market share to 11 %. Energy wood on the other hand has a decreased market share in the alternative scenario. Even though the energy wood use has increased, the flow is only responsible for 14 % of the feedstock market.

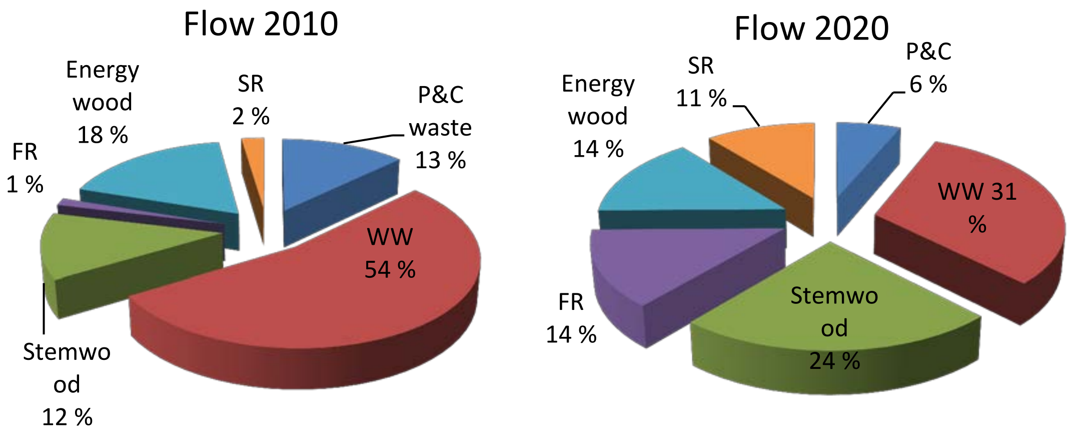

Figure 25: energy breakdown (in percentage of GWh flows) for the six feedstocks assessed for the reference and alternative scenario respectively.

Figure 26 shows the flow of pre-treated materials for both the reference and alternative scenario. Chips dominate the Norwegian market for bio-treatment, with 97 % market share in the reference scenario. Today, torrefaction is not used in Norway. Pellets have experienced increased production the latter years, but still only accounts for 2 % of the market. Direct combustion of saw residues by the wood processing industry has a small share of only 1 % in the assessed system. Moving on to the alternative scenario, the picture is quite different than what was the case for the reference scenario. Figure 26 shows that the chips share has decreased quite substantially to 61 % in the alternative scenario. The remaining three pre-treated materials are experiencing increased use. Pellet and TOP have increased to 20 and 16 % respectively, compared to 2 % and 0 % in the reference scenario. The saw residues use has increased to 3 % in the alternative scenario.

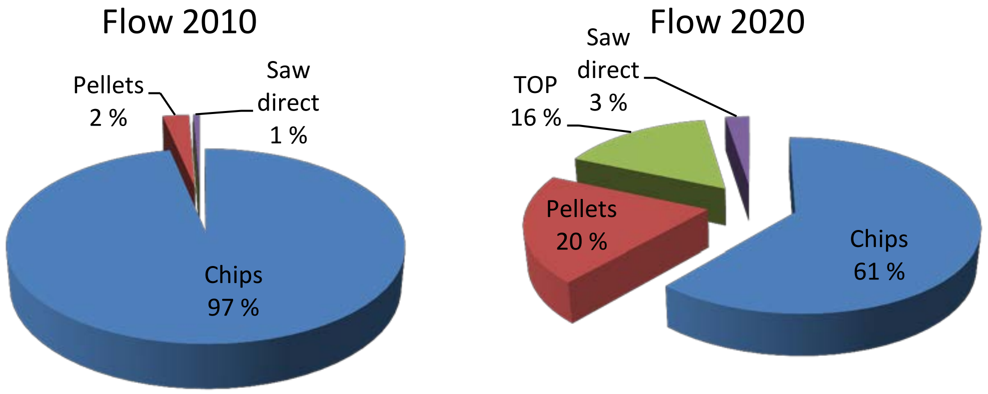

Figure 26: energy breakdown (in percentage of GWh flows) for the four pre-treated products for the reference and alternative scenario respectively.

The energy service flows are presented in Figure 27, showing the amount of electricity, heat and steam in the reference and alternative scenario respectively. Heat has the highest share in both the reference and alternative scenario, accounting for 76 and 69 % of the total flows respectively. Electricity distribution accounts for 23 % of the bio-market in both scenarios. Steam has a small share in both scenarios, with 1 % of the total flow in the reference scenario and 4 % in the alternative scenario. The share of the different energy technologies remains the same for both CHP, district heating and thermal power plant, while the use of direct saw residues leads to increased steam production. This is reflected in the rather constant heat and electricity share, but an increase in steam to 4 % in the alternative scenario.

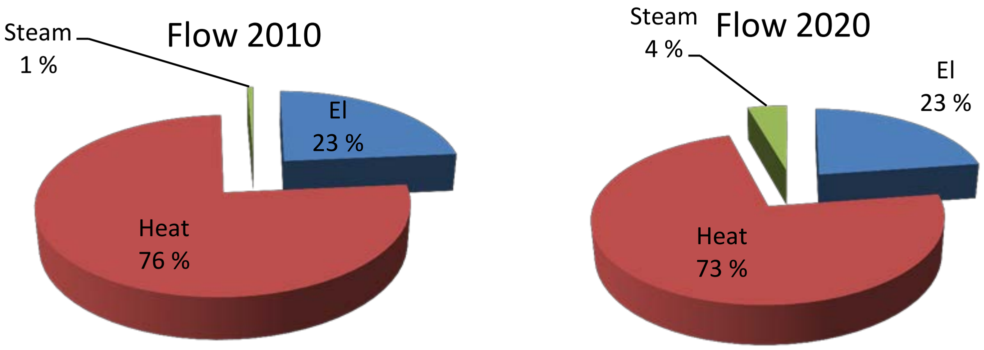

Figure 27: energy breakdown (in percentage of GWh flows) for the different energy services for the reference and alternative scenario respectively.

6.2.2 Global warming potential

Combining the impacts of each of the 80 possible value chains analysed with the material flows, give the scenario results. All GWP results presented include albedo effects. Figure 28 presents the total bioenergy flows (in GWh) and total GWP for both the reference and alternative scenario. The current Norwegian bioenergy system assessed gives a GWP of 134 grams CO_2-equivalents per kWh. This implies a total climate change impact of 0,58 million tonnes of CO_2-equivalents for the 4,3 TWh produced bioenergy in 2010. The alternative scenario has a climate change impact of 136 grams CO_2-equivalents per kWh, or 1,15 million tonnes of CO_2-equivalents. The total bioenergy flow assessed in the alternative scenario is 8,3 TWh. The GWP results for both the reference and alternative scenario are discussed below, categorised by feedstock, treatment option and end use. The differences between the two scenarios will be tracked, before comparing the total values further.

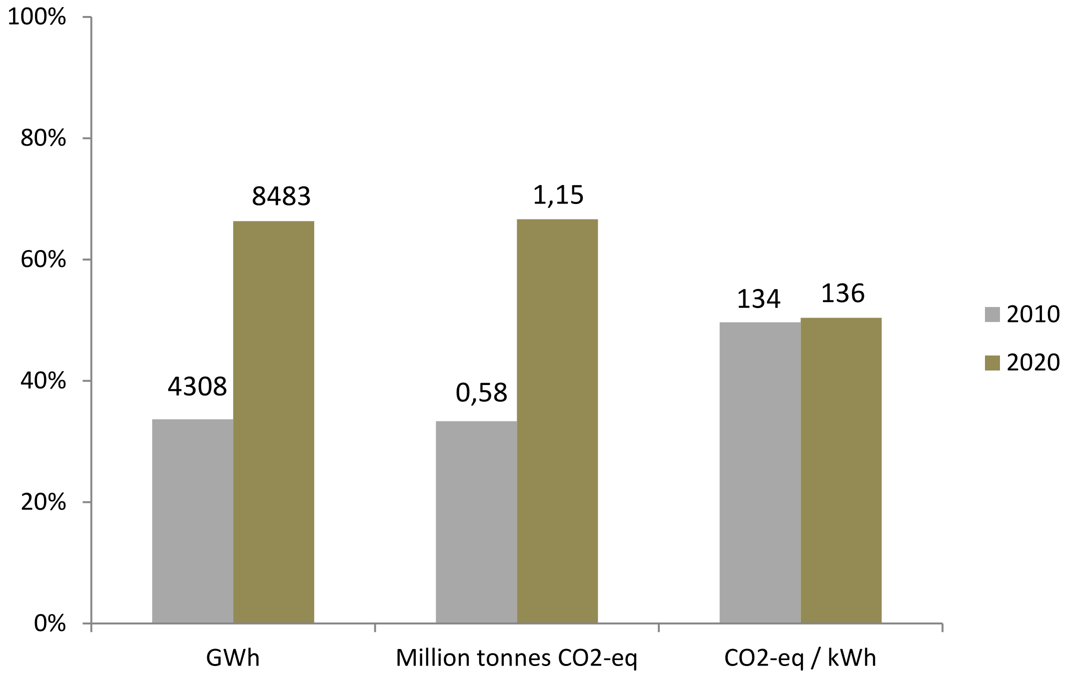

Figure 28: total energy flow and GWP for the reference (2010) and alternative (2020) scenario, normalised to the sum of the two alternatives.

As for the materials flows, the GWP results will be presented for feedstocks, treated materials and energy services. Figure 29 shows the results for the reference and alternative scenario categorised by feedstock. Waste wood is responsible for the bulk of the impacts for both the reference and alternative scenario, 44 and 31 % respectively. Waste wood was also accounting for the bulk of the feedstock flows - 54 and 31 % respectively for the reference and alternative scenario. For the reference scenario, the second biggest contributor to GWP is stemwood accounting for 23 % of the total GWP. Energy wood and forest residues are responsible for 10 and 3 % of the total GWP respectively. Forest residues have a low market share in the reference scenario, with a use increasing towards 2020. In the alternative scenario, forest residues therefore have an increased GWP share to 11 %. The stemwood share of GWP accounts for 23 % also in the alternative scenario, while energy wood has an increased share to 12 %. All the forest resources have an increased use towards 2020, which is reflected in the increase in GWP share. Finally, saw residues have quite a substantial increase in GWP share towards 2020, increasing from 4 to 14 %. All the forest resources, including saw residues, have higher impacts than both energy wood and waste wod. Combining this with the fact that wood waste has a low increased use towards 2020, the GWP share of waste wood is decreasing towards 2020. P&C waste experiences no increased use towards 2020, which is reflected in the decrease in GWP share.

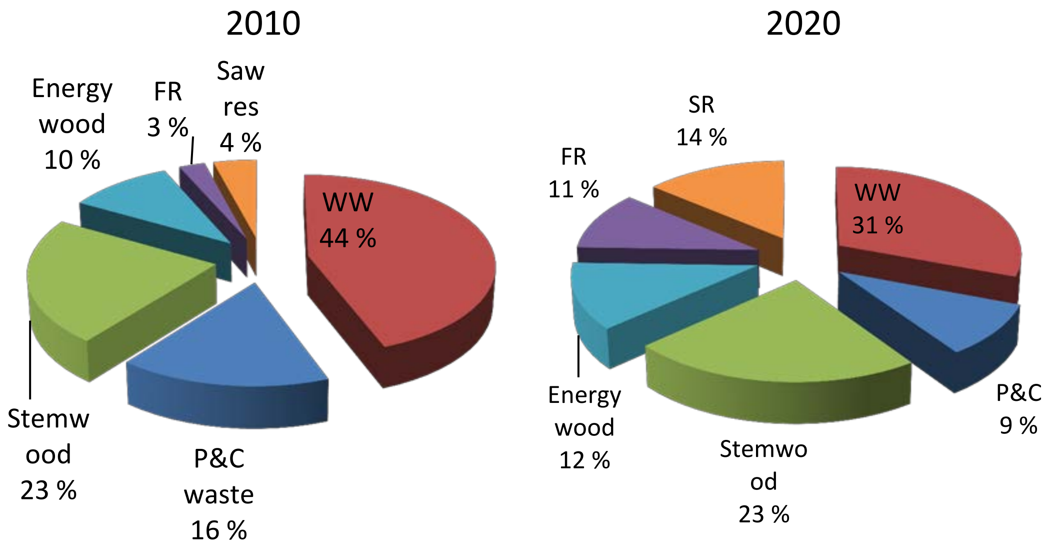

Figure 29: climate change impact (in percentage of CO_2-equivalents) for the feedstocks in the reference and alternative scenario respectively.

Figure 30 shows the GWP categorised by pre-treated materials, and the picture is quite different for the reference and alternative scenario. Chips also dominate the GWP from biomass pre-treatment, accounting for 96 and 60 % of the impacts in the current and alternative scenarios, respectively. Torrefaction is not used in Norway today, but the assessed use towards 2020 implies a GWP share of 23 %. A pellets production increase is also evident towards 2020, leading to a share of total GWP increasing from 3 % in 2010 to 14 % in 2020. The direct saw residues case have a GWP share of 1 % in 2010, increasing to 3 % in 2020..

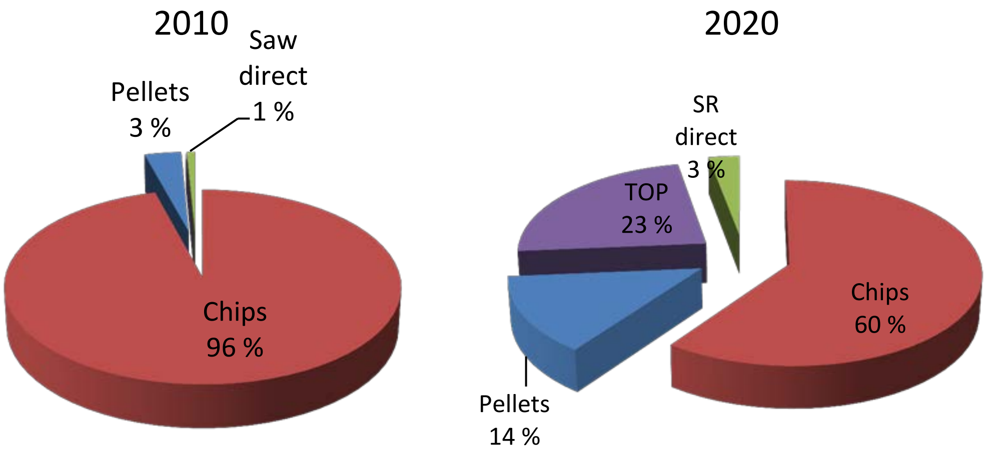

Figure 30: climate change impact (in percentage of CO_2-equivalents) for the treated materials for the reference and alternative scenario respectively.

Figure 31 shows the GWP categorised by the different end uses. Heat is responsible for the bulk of the market, and also the bulk of the GHG emissions, accounting for 69 and 68 % in the reference and alternative scenario respectively. Electricity is responsible for 30 and 29 % in the current and alternative scenario. The share of materials going to the different conversion technologies is constant for all technologies except the steam producing boiler. The amount of saw residues going to direct combustion increases in the alternative scenario, reflected by the increase in GWP share for steam towards 2020, which increses from 1 % in 2010 to 3 % in 2020.

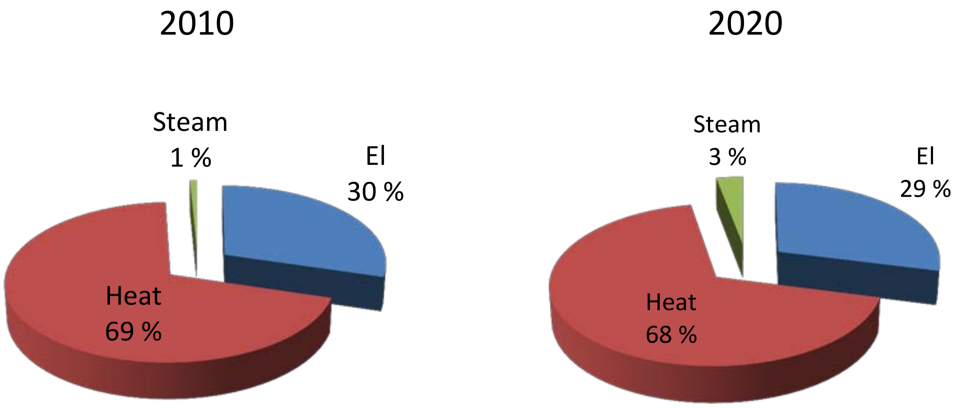

Figure 31: climate change impact (in percentage of CO_2-equivalents) for the energy services for the reference and alternative scenarios respectively.

Going back to Figure 31, it should be stressed that the increase in bioenergy production is for the assessed feedstocks. The 14 TWh goal includes more feedstocks, as there are Norwegian biomass resources that are not included in this study. These resources will most likely not experience an increase as high as the assessed feedstocks. In this thesis, a 48 % increase in bioenergy use is modelled from 2010 to 2020, and this increase results in an increase in absolute GWP of 36 %. The GWP expressed per functional unit shows a slight increase from 2010 to 2020 – about 1.5 %. This means that the high increase in total bioenergy use modelled, results only in a slightly increased GHG effective system. The reason for this is due to a beneficial use of the assessed value chains, where the feedstocks utilised for bioenergy production is the main reason. The increase in forest resource use is substantial; the relative increase is 74 % for stemwood, 45 % for energy wood and 95 % for forest residues. Energy wood is stated to be the most advantageous for bioenergy production, see Figure 17. The increase in climate change impact in the alternative scenario is based on the high increase of both stemwood and forest residues, which are less beneficial than both energy wood and wood waste. Also saw residues have a high increased use, a 90 % relative increase. This is reflected by the higher share of climate change impact of steam in Figure 31. Wood waste only has an increased use of 15 %, while P&C waste use remains constant towards 2020. The waste resources have quite low impacts, where wood waste is the second most beneficial feedstock regarding GWP. Saw residues are stated to be more beneficial for bioenergy production than both stemwood and forest residues. Looking at treatment option, pellets production is stated to be the most beneficial - also one of the reasons for the low GWP relative to produced energy in the alternative scenario.

Inclusion of both surface albedo effects and biogenic CO_2 emissions affect the scenario results substantially. Not including albedo effects would result in higher GWP for both scenarios, i.e. 144 and 152 grams CO_2-equivalents per kWh for the reference and alternative scenario, respectively. The relative difference between the alternative scenario and reference scenario would be high including albedo effects, i.e. 5 %. These GWP values, not including albedo effects, support what is already stated; the high increase of forest resource extraction towards 2020 is the main reason for the increase in GWP for the alternative system (the albedo effects only change the GWP for the forest resources). Looking at the absolute values, the total GWP is 0,62 and 1,29 million tonnes of CO2-equivalents for the reference and alternative scenario, respectively not including albedo effects.

7 DISCUSSION AND CONCLUSION

This study set out to assess the environmental impacts for a set of Norwegian bioenergy value chains, and construct these to represent a current reference scenario as well as a future alternative scenario. A set of feedstocks, pre-treatment choices, energy conversion technologies and energy distribution options were assessed and put together to a total of 80 value chains. Life cycle assessment was used to evaluate the environmental performance of the modelled systems. Accurate evaluation of global warming potential was a core task, and GWP_{bio} factors have been assigned to all biogenic CO_2 emissions accounting for its climate change impact. Surface albedo effects for forest resources and storage emissions from biomass decay have also been included in the assessment. In addition to climate change impact, the impact categories of acidification potential, particulate matter formation potential and terrestrial ecotoxicity potential have been assessed.

The results showed that using energy wood or waste wood as biomass resource had clear advantages over the remaining feedstocks for GWP. Including surface albedo effects, the difference in impacts between energy wood and stemwood, forest residues and saw residues were reduced. Pelletising was the most preferable treatment option, and integrated torrefaction and pelletising was the treatment option causing the highest climate change impacts. Investigating the energy conversion technologies, the thermal power plant producing electricity was the option resulting in highest GWP, while the CHP plant with electricity demand was the lowest.

Acidification potential showed a somewhat similar picture as GWP; the thermal, electricity option was the least preferable and the CHP, electricity option the most. Integrated torrefaction and pelletising showed high impacts while the chips systems performed well. Forest resources performed poorer for all impact categories. For PMFP and FETP, the heat producing units had the highest impacts, and chipping was the advantageous pre-treatment choice. Saw residues and the waste resources performed best for AP, PMFP and FETP. Out of the three forest resources, forest residues had the highest impact for all of the four impact categories assessed.

This chapter will discuss the results presented in this report and investigate the implications of these results. The result evaluation will be divided in a discussion of key assumption, investigating the modelled system and the most important assumptions, and an external benchmarking, comparing the results in this thesis to available literature. The implications of the results will then be presented and recommendations for Norwegian bioenergy will be given. Finally, a conclusion is presented.

7.1 Key model assumptions

Starting with feedstocks, six resources are modelled and assessed. The forest resources come out as preferable options regarding GWP when albedo effects are included. Excluding such effects, energy wood and wood waste are the preferred options. Waste resources only require collection prior to treatment, where the forest resources require resource harvest, forwarding to forest road and storage in both forest and at forest road. Diesel use during harvest and forwarding is important for the feedstock impacts, and are updated according to Norwegian conditions. For forest residues, the impacts from bundling are high. The financial cost of forest residues bundling is also very high (Valente et al., 2011) , questioning the bundling process. Therefore, further investigation of forest residue bundling is important. Updating the bundling process with real-case, Scandinavian values would offer greater insight to the environmental burdens of such cases. Scandinavian data for wood resources and saw residues collection would also be beneficial for the assessed system.

Forest residues harvest is assumed harvested integrated with stemwood harvest. Mass allocation based on biomass expansion factors is applied for the two feedstocks to allocate the harvest impacts. If the forest residues were not harvested, the residues would be left in forest to decay. This would result in GHG emissions. The benefit of utilising the forest residues is not included in the assessment. Leaving some residues in forest is important for nutrient recycling, and the 15 % dry-matter losses from storage in forest comply with this. Some needles, leaves and branches will fall off and the nutrients are left in forest.

Energy wood is the most advantageous feedstock for GWP, even though surface albedo effects are not included for this feedstock. The main reason for the low impacts from the energy wood value chains is the low GWP_{bio} factor assigned to this resource compared to the other resources. The rotation period is the determining parameter for the GWP_{bio} factors for the forest resources. Integrated stemwood and forest residue harvest imply a GWP_{bio} factor of 0.43, as harvest takes place at the end of the forest rotation period. The energy wood case is quite different; the GWP_{bio} factor is 0.11, and regrowth right after harvest is assumed, i.e. regrowth after 20 years. This is in fact not the case for in-forest thinning. For thinning at road-side, this assumption will hold. The thinning wood considered in this thesis is a combination of in-forest thinning, thinning at road-side and thinning under power lines. For the latter two, the GWP_{bio} factor used is representative, but for the former, the GWP_{bio} factor should in fact be higher.

For energy wood harvest in-forest, the regrowth will not start before 80 years after harvest – for a 100 years rotation period. For the first 80 years after harvest, the CO_2 pulse will be similar to a fossil CO_2 pulse, while the biomass will regrow the next 20 years. If these effects are included, the GWP_{bio} factor would be lowest for thinning occurring late in the rotation period. On the other hand, using a GWP_{bio} factor for in-forest thinning, the impacts would be overestimated as the thinning considered is a combination from several resources. Comments should also be made regarding surface albedo effects for energy wood. Albedo effects are not included for energy wood, even though such harvest changes the surface albedo. The reason for not including albedo effects for energy wood is lack of albedo calculations for this feedstock. If included, the mean annual albedo for pre-harvested energy wood is lower than what is the case for stemwood, forest residues and saw residues harvest. The overall benefit of including surface albedo effects would therefore be lower than for clear-cut.

Looking at paper and cardboard waste and wood waste, the GWP_{bio} factors used for the two resources is the main reason for the difference in impact between the two feedstocks. Wood waste is assigned a lower GWP_{bio} factor, as the storage time in the anthroposphere is longer. Wood waste is a large resource category, and could have been divided between several product categories. Different storage times in the anthroposphere would apply for different end of use products. Looking at three different cases; a short storage time, a medium storage time and a long storage time, a storage time of ten years would be applicable for the short storage time case (Malmsheimer et al., 2008). Railroad ties, wooden container and pallets are examples of products falling into this category. A medium storage time would be 30 years, and furniture waste is a product category example. The long storage time would be 100 years, where single-family homes are the end of use product. Construction waste would most likely have an assumed storage time shorter than the short storage time case. In this thesis, a storage time of ten years is applied for wood waste. Increasing the assumed storage time in the anthroposphere would decrease the GWP_{bio} factor.

Therefore, splitting the wood waste product category in this thesis in several wood waste categories would imply different results. Wood waste cases stored in the anthroposphere for a sufficiently long time could imply GWP_{bio} factors resulting in net climate cooling effects. Albedo effects are not included for the waste resources. Both P&C waste and wood waste originate from forest, and albedo effects should therefore be included. As for energy wood, assumptions regarding albedo effects are difficult to make, as the albedo effects has not been assessed. If included, the climate change impact from waste resouces migh be considered negative.

When including GWP_{bio} factors, uncertainties arise; for energy wood, type of thinning is important, while for wood waste, storage time in the anthroposphere is important. Stemwood, forest residues and saw residues are assigned the highest GWP_{bio} factors, as the rotation time is the longest. The biogenic CO_2 emissions from the value chains utilising these three resources are therefore assigned a higher impact. Including the climate effect of biogenic CO_2 emissions though is important to assess the sustainability of biomass systems. The share of biogenic CO_2-equivalents to fossil CO_2-equivalents are found to be high in this thesis, which points to the importance of treatment of biogenic CO_2 emissions in LCA studies. The same reasoning can be applied for both surface albedo effects and GHG emissions from biomass storage; there are uncertainties, but it is important to include as many sides of the biomass system as possible to assess the proper climate change impact.

Surface albedo effects reduce the climate change impact substantially for the stemwood, forest residues cases and saw residues cases. Including such effects are important to model an accurate GWP from boreal forest. Not including surface albedo effects, the climate change impact of Norwegian forest is considerably higher. Albedo effects are as mentioned not included for energy wood or waste resources. This is recommended for a more complete climate change impact from Norwegian forest. Surface albedo effects are normalized to the biogenic CO_2 emissions from the systems. This means that there is no differentiation between the albedo effects for the different value chains beyond differences in total GHG emissions. Calculating the surface albedo effects based on the yields for the different value chains would result in a higher degree of differentiation between the value chains. For instance, chipping is the treatment option with the lowest yield, and would therefore experience the highest benefit of including albedo effects based on value chains specific yields. In the assessment of albedo effects in this thesis, a GWP factor is found and applied likewise for all value chains, while expressing the GWP benefit per hectare forest would imply a need for the value chain yields.

Looking at the treatment options and resulting products, pellets and chips are advantageous over integrated torrefaction and pelletising. Pelletising is further advantageous over chipping. Chips storage time is an important assumption in this thesis; for the chipping case, a chips storage time of six weeks is assumed, while chips storage prior to pelletising or integrated torrefaction and pelletising only has a time frame of two weeks. The results indicate the benefits of further treatment, as this reduces losses and decay – neither pellet nor TOP have any storage losses or emissions. Since biogenic CO_2 emissions are accounted for, storage emissions are important for the biomass systems. Regarding chips storage, biomass storage pile height is an important factor, which both CH_4 and N_2O emissions are dependent upon. Cherubini and Strømman (2011) state the importance of inclusion of N_2O emissions from dry matter losses, as discussed in the introduction, and stress the uncertainties in the N_2O emissions caused by the stressor's high GWP – 298 times greater than CO_2. In addition, N_2O emissions are very sensitive to the height of the chips storage pile chosen, and in the case description section several values for pile height are indicated. The chosen value for the storage pile height is ten meters, and choosing a lower value would increase the N_2O emissions substantially. Therefore, real-case values for chips storage pile height would strengthen the certainty of CH_4 and N_2O emissions from chips storage.

The difference between chips, pellet and TOP is also a result of recovery rates. Chipping is inefficient because of high dry-matter losses, and the chips value chains therefore require more resources from forest. Overall, densities, heating values and moisture contents are important parameters for the different materials. This means that where in the value chain treatment takes place and where in the value chain moisture content reduction takes place is important. As discussed in the theory chapter, chipping can occur in several places of the value chain. Decreasing chips storage time is important for the GWP because of decay and emissions of CO_2, CH_4 and N_2O. In this manner, the closer to combustion chipping takes place, the more advantageous. Chipping on demand is therefore beneficial for chips systems. In this thesis, chipping is performed at energy conversion site. Also the direct saw residues case is transported directly to conversion site, where storage takes place. Pelletising and integrated torrefaction and pelletising are pre-treated at separate facilities, with transport to this facility and from treatment site to combustion site. The choice of transport in the value chains is therefore adapted to the different pre-treatment options, which creates a credible and realistic picture for the treatment technologies.

Densities and heating values are important parameters also for transport. The impacts from transport are quite low in this thesis – differing substantially for the different materials transported. The transport distance from forest road/collection to treatment facility is 40/20 kilometres respectively, while the transport distance from treatment site to conversion site is 80 kilometres. The waste resources and saw residues have therefore a lower transport distance to treatment facility, implying lower GWP impacts for the transport step. Also, the feedstocks going to chipping and the saw residues going to combustion only have one transport distance, as chipping and saw residues storage takes place at energy conversion site. Impacts from transport to conversion facility differ quite extensively for the different pre-treated materials; TOP is the most advantageous material to transport. Chips would be the least advantageous to transport - one of the reasons why chipping at energy conversion site is beneficial. The large difference in transport impacts from the different materials transported point to the benefits of treatment for biomass value chains. It has been argued that the transport distance will be somewhat longer in the future than what is the case today (Kärhä, 2011). In this manner, transport of TOP and pellets will be more advantageous than what is the case for chips. Kärhä (2011) further states that a more efficient means of long distance transport is required. TOP and pellets offer good opportunities, independent of feedstock used for TOP and pellet production, as the transport will be more efficient.

The difference between the GWP results for the conversion technologies presented in the result chapter is mainly based on the differences in conversion efficiencies. The thermal power plant has the definite lowest conversion efficiency; 36 %, while the CHP plants have the highest efficiency; 90 % total. The modelled energy conversion units represent mature technologies. The results point to the importance of combustion technology choice, as the relative difference between the unit with highest and lowest total efficiency is 60 %. Comparing the results for the thermal power plant producing electricity and the CHP plant with electricity demand, the former has an average GWP 55 % higher than the CHP option. The difference between the heating units is smaller, as the efficiencies for the units are closer.

Electricity inputs differ for the heating and electricity options. The electricity inputs are modelled from two plants, where the Nordic electricity mix is used. Generally, electricity use is of importance for the results throughout the entire value chain, particularly the direct inputs to pre-treatment and energy conversion. The impacts of electricity use are sensitive to assumptions of where the electricity is produced. Differentiation is also applied for infrastructure for the heating and electricity units. Emissions from energy conversion is differentiated between clean and waste wood, for both operational emissions to air, condensate emissions and emissions from ash disposal. Differences between clean and waste wood are applied for the torrefaction alternative as well. This differentiation is important assessing the impact from waste compared to clean wood. Differences in emission factors – in particular air emission from operation, for the five different combustion technologies would contribute to a further differentiation between impacts for technology choice.

When investigating energy systems in a life cycle perspective, all processes and emissions in the entire value chain should be accounted for. This is performed for the assessment in this report, updating diesel use and emissions from both extraction and forwarding in the forestry step, including GHG emissions from all storage steps throughout the entire value chain, accounting for biogenic CO_2 emissions and integrating Nordic electricity mix throughout the value chains. Transport and treatment options are adapted for the different value chains, while air emissions and emissions from ash disposal are updated for the torrefaction process and all combustion options. Also, condensate emissions are updated for the energy conversion units, and all emission factors for the ten conversion options are specified for clean and waste wood. Also the torrefaction process differentiates between clean and waste wood. The inputs to the energy conversion step are modelled to represent a CHP plant fuelled by biomass. The overall advantage of this assessment is the inclusion of GHG emissions throughout the entire value chain, specified heavy metal emissions for clean/waste wood, inclusion of biogenic CO_2 emissions and surface albedo effects – all modelled to represent a *Norwegian system*.

The scenario analysis shows that a doubling of biomass use will lead to a small increase in GWP per kWh. It should be stressed though, that there is modelled a doubling of biomass use for the assessed feedstocks, which implies about ten TWh new bioenergy. The low GWP increase in the alternative scenario points to the fact that desirable value chain options have a high potential increase. The feedstocks utilised today are the ones that are most economically viable. Economic potential is not directly included for the potential increase, but values for theoretical potential are used, which subtracts the resources which are too expensive. The increase in waste is very low, and the increase in forest resources is very high. The forest resources have the lowest GHG impact of all the feedstocks, resulting in a beneficial alternative scenario towards 2020. The change in GWP for the alternative scenario would therefore be larger had the increase in feedstock been different. Increased pellets use is also one of the reasons why a more beneficial alternative scenario is evident. The substantial increase in TOP use (from zero) and increase in use of saw residues, are reasons to why the difference between the two scenarios are so small.

The low impacts from chips compared to chips flows in the scenarios are a result of the substantial use of feedstocks with low impacts. Forest resources and waste wood contribute 38 and 51 % respectively to chips production in the alternative scenario. In the reference scenario, waste wood contributes to 55 % of the total inputs. Waste wood is one of the preferred feedstock in a GWP perspective. For pellets, the picture is different; saw residues are one of the main inputs for production, accounting for 99 and 28 % of the inputs for the reference and alternative scenario respectively. Saw residues cause a higher impact than what is the case for wood waste. This is why the GWP share is higher than the flow for pellets in the reference scenario. In the alternative scenario, feedstocks causing a lower GWP are the main inputs, where forest resources accounts for 71 % of the inputs to pellets production.

The scenario model is not accounting for imports and exports to the Norwegian market. The assessed flows are the ones *present in the Norwegian market*, meaning that all flows are assumed produced in Norway. This is not necessarily the case. For pellets for instance, both imports and exports are present. The imported pellets have a different climate change impact than the pellets produced in Norway. Therefore, including imports and exports and coherent climate change impact would improve the scenario results. Including imports and exports are thought to be of greater importance for a future scenario, as TOP will be more beneficial to transport. Chips are stated to not be suited for transport, and Norwegian regulation prohibit waste export. Also, integrating the process LCA results with the Norwegian economy could offer interesting insight, i.e. constructing a hybrid LCA model of Norwegian bioenergy.

7.2 Model robustness

The results presented in this thesis will now be compared to available literature. Many have investigated Norwegian bioenergy towards 2020, but to the author's knowledge, the total climate change impact has not been evaluated. Some of the value chains will therefore be compared to other studies. Raymer (2006) found that demolition wood combusted in a district heating plant had the lowest impact of six Norwegian value chains. The GWP was found to be about 110[1] grams CO_2-equivalents per kWh. In this study, the GWP for chipped waste wood combusted in a district heating plant was found to be 122 grams CO_2-equivalents per kWh. The results for chipped waste wood were lower than all the feedstocks except energy wood. Raymer (2006) assumed biomass to be carbon neutral, but included methane and N_2O emissions from combustion. The two values for wood waste combustion in a district heating plant were quite close - higher in this thesis because of inclusions of biogenic CO_2 emissions. Eriksson et al. (2007) also state that waste resources have the overall greatest GWP savings. Further, Raymer (2006) found the climate change impact from sawdust combusted directly to be 24[1] grams CO_2-equivalents per kWh, and saw residues pellets to be 13 grams CO_2-equivalents per kWh. In this thesis, the equivalent value chain gave GWP of 158 and 156 grams CO_2-equivalents per kWh respectively. The main reason for the large difference is still because of inclusion of biogenic CO_2 emissions. The results in this study aligned with Raymer (2006) in the way that saw residues pellets were more beneficial than direct combustion of saw residues.

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[1] *: based on the yield found for the value chains in this thesis.*

Looking at chips systems, Wihersaari (2004) found life cycle GHG emissions from forest residues collection from final harvest combusted in a modern CHP unit to be 6-9 grams CO_2 equivalents per kWh. Forsberg (2000) found a GWP of 26 grams CO_2-equivalents per kWh electricity for a tree section case, while for a baled forest residue case the GWP was found to be 34 grams CO_2 equivalents per kWh. Biogenic CO_2 emissions were not included in these assessments, and the results in this thesis are therefore higher. In this thesis, forest residues chips combusted in a CHP plant with electricity demand was found to be 165 grams CO_2-equivalents per kWh, while for chipped energy wood the GWP found was 51 grams CO_2-equivalents per kWh.

Pellets impacts in this study were found to range from 50-356 grams CO_2-equivalents per kWh for electricity production, the higher values for combustion in a thermal power plant with electricity demand. For heat production, the GWP values range from 52-166 grams CO_2-equivalents per kWh for pellets production. The lower values are found for energy wood for both electricity and heat, while the higher values are found for the value chains utilising forest residues. Many have assessed the climate change impact from pellets, and Forsberg (2000) reports 32 grams CO_2 equivalents per kWh. Hagberg et al. (2009) found GWP for pellet to be in the range of 10-14 grams CO_2-equivalents per kWh for Swedish conditions - assessing roundwood, wet sawdust and dry saw shavings as inputs to production. Also Sikkema et al. (2010) investigated pellet production from saw residues and found a GWP of about 11 grams CO_2-equivalents per kWh for large-scale pellet use in district heating plants, and a GWP between 36 and 70 grams CO_2-equivalents per kWh for large-scale power production in the Netherlands. Sjølie and Solberg (2011) assessed the GHG emissions from Norwegian wood pellet, and found life cycle GWP between 24 and 482 kg CO_2-equivalents per kWh, where the lower end of the GWP is for raw materials supplied locally and the higher end included pellets import from Canada. The main difference between values is obviously treatment of biogenic CO_2 emissions. Forest residues are the feedstock causing the highest emissions of biogenic CO_2 in this thesis, mainly because of a high GWP_{bio} factor. The difference between stemwood and forest residues is low. The lower values for the pellets value chains assessed in this thesis is in accordance with some of the indicated studies above.

Both Eriksson et al. (2007) and Cherubini and Strømman (2011) stated that CHP plants are the best option for biomass conversion. This is in accordance with what was found in this thesis, where the CHP plant with electricity demand had the lowest impacts for all conversion technologies assessed. A CHP plant with heat demand was also a better option than district heating for both GWP and AP. Gustavsson (1997) compared heat and electricity production from biomass, and stated that less efficient systems led to greater CO_2 emissions for systems including biogenic CO_2 emissions. This was also one of the main findings regarding energy conversion technologies in this thesis; the conversion option with the highest GWP impact is also the option with the definite lowest conversion efficiency.

Guest et al. (2011) reported greenhouse gas emissions in the range 8,9 – 10,5 grams CO_2-equivalents per MJ electricity delivered to end users. Compared to the result of this assessment, the GWP were considerably higher in this thesis. The main reason for this being handling of biogenic CO_2 emissions, and in addition the greenhouse gas emissions included for storage - particularly from chips storage. In the study performed by Guest et al., the technology used is CHP gasification, which has a higher overall operational efficiency, and the transportation distances used in the same study are lower than the distances used in the analysis performed in this study. Investigating energy distribution, heat distribution was found to have the highest impact in this thesis, mainly because of excavation need and material inputs.

The main difference between this study and literature is inclusion of biogenic CO_2 emissions, which affect the GWP substantially. Guinée and Heijungs (2009) state that handling of biogenic CO2 emissions is of great importance for the LCA methodology. This is also evident from the comparison carried out here. Also N_2O and CH_4 emissions are stated to be of significant importance in LCA (Cherubini, 2010; Cherubini et al, 2009). Storage emissions are stated to be of high importance in this thesis – in particular for the chips systems, which include CO_2, CH_4 and N_2O emissions from biomass decay. Inclusion of albedo effects also affects the results substantially. The overall GWP from the forest resources is reduced by 20 % including these effects.

In order to put the results of this assessment in perspective, Table 29 shows the GWP from several energy producing technologies – both fossil and renewable. The values given are all calculated in a life cycle perspective. Benchmarking the total scenario results to these GWPs will indicate the overall environmental performance for the system analysed in a broader perspective.

GWP from energy production [g CO2-eq / kWh]	
Natural Gas Combined Cycle	425 [a)]
Natural Gas Combined Cycle with CCS	125 [a)]
Coal (BAT) [c)]	840 [b)]
Coal (BAT) with CCS [c)]	220 [b)]
Wind	12-16 [d)]
Hydro	4-10 [d)]

Table 29: GWP from several alternative energy producing technologies.
[a)] (Singh et al., 2010)

[b] (Singh et al., 2011)
[c] Supercritical BAT (Best Available Technology)
[d] (Weisser, 2007)

The GWP for the reference and alternative scenario is respectively 134 and 136 grams CO_2-equivalents per kWh. Comparing this to the GWP for several energy sources indicated in Table 29, the bioenergy system assessed performs better than all the fossil resources except the natural gas combined cycle with CCS. Inclusion of albedo effects demonstrates its importance here; excluding such effects, the scenario results in this thesis would be 7 % higher for the reference scneraio and more than 10 % higher for the alternative scenario. Comparing the GWP of the reference and alternative scenario to other energy sources, the overall climate change performance is substantially worse than the renewable energy technologies wind and hydro. The relative difference between GWP for a natural gas combined cycle and the reference scenario is 68 % - which is in accordance with the stated GHG reduction in the introduction (ECF et al., 2010). Looking at the different value chains assessed for the total system, the value chain with the highest impact, forest residues TOP combusted in a thermal power plant with electricity production, has a GWP of 410 grams CO_2-equivalents per kWh; only 3.5 % lower than a natural gas combined cycle without CCS. Comparing the results in this thesis to the fossil energy options with CCS, all other environmental impact categories increase with the use of CCS (Singh et al., 2010). On the lower end of the GWP found in this thesis, energy wood chips combusted in a CHP plant with electricity demand has a total GWP of 51 grams CO_2-equivalents per kWh – lower than all the fossil energy sources, but still 73 % higher than the average GWP from wind power.

7.3 Implications

The results found in this thesis question the environmental benefit of biomass for energy production. The biomass systems are not assumed climate neutral, which results in high climate change impact. It is therefore important to assess the sustainability of bioenergy systems, and develop a bioenergy market based on the value chains which are the most advantageous. The Norwegian Government has ambitions of decreasing the GHG emissions substantially towards 2020, and choosing a bioenergy path with low impacts is therefore crucial. This section will suggest developments for the assessed model in this thesis, present recommendations for Norwegian bioenergy and suggest further research.

Developing a model including all (or more) parts of the Norwegian bioenergy market would offer a more complete picture of the Norwegian bioenergy system. In addition, to reach the 14 TWh goal, more feedstocks, treatment and enduse options must be included in the model, as the modelled increase in this thesis is only 4,2 TWh produced bioenergy, or 10 TWh biomass going to bioenergy. There are several feedstocks that are not included; agricultural residues, biogas, agricultural crops, straw, aquatic crops, more by-products from industry and municipal solid waste. Starting with the latter, large amounts of the municipal solid waste are derived from biomass resources, e.g. paper, cardboard, wood waste, yard waste and food waste. Paper, cardboard and wood waste are included in this thesis. Saw residues from the wood processing industry are also included in this study, but black liquor and bark from industry are not included. Agricultural crops are not used for energy production in Norway, and neither are aquatic crops. Some feedstocks would improve the modelled system, them being agricultural residues, biogas and bark. Biogas and agricultural residues are stated to have a potential increased use towards 2020, reaching the goal of 14 TWh new energy. Biogas is particularly interesting as the Norwegian Government has a goal of increasing the use of biogas (Regjeringen, 2011). Even though, the most important development of the model would be including logs for residential heating. This is an important part of the Norwegian bioenergy system, amounting to 8,3 TWh of the bioenergy use in 2010 – or 47 % of the total bioenergy use. Logs for residential heating is assumed to experience less increase towards 2020, as district heating is foreseen to be of great importance. Central biomass combustion for energy will also reduce for instance particulate matter emissions, as the combustion is better optimised.

Developing and increasing the bioenergy use in Norway, some value chains show clear benefits. Taking into account that electricity, heat and steam production is desired, recommendations will be made including all enduse options. Looking at electricity options, the thermal energy plant with electricity demand shows the definite highest impact for both GWP and AP. Also for PMFP and FETP, this option has the highest impact of the two electricity options assessed. Therefore, for electricity production, CHP is the recommended alternative. CHP plants can either be operated with electricity demand or heat demand (Loo and Koppejan, 2007), and the option of electricity demand is recommended. Comparing the two CHP options, the electricity demanding option has the lowest impact for all impact categories assessed. Difference between the two CHP options is mainly based on the impact from energy distribution.

Based on the low impacts from the CHP plant, use of torrefied pellets is recommended for this conversion technology. To pursue a use of TOP for combustion for energy, this should take place in an energy conversion option with low impacts to limit the overall impact of the value chains. TOP is the treatment technology resulting in the highest impact, and if used in a CHP plant, the impacts after treatment are limited. For steam production, saw residues is the feedstock used today. It is foreseen that this also will be the case in the future, as steam is used by industries which also produces the by-product of saw residues. It is found that pelletising saw residues gives lower impacts for GWP, and it is recommended to pursue further treatment of saw residues in the future. Saw residues pellets offer high flexibility, as storage can take place without any dry-matter losses or GHG emissions.

Today, waste resources, chips and pellets are combusted in district heating plants (Langerud, 2007). In this thesis, energy wood and wood waste come out as the best options regarding GWP. Pellets are found to cause the lowest GWP of the treatment options. Eliminating the thermal, electricity option because of high impacts, the district heating plant is the energy conversion option resulting in highest impact for both GWP and AP. Also for PMFP and FETP, the heating options have the highest impacts. Therefore, combustion of waste and pellets in district heating plants is recommended to be pusued also in the future. Also energy wood is recommended for use in district heating plants because of the feedstock's low climate change impact. Because of the quite high impacts from forest residues, stemwood and saw residues compared to energy wood and waste wood, it is recommended that these feedstocks are utilised in the most GHG efficient conversion route. The CHP option with electricity demand and the steam producing boiler cause the lowest impact of the assessed conversion options. Therefore, forest residues and stemwood combustion is recommended to take place in a CHP plant. Today saw residues are combusted difrectly for steam production, and this is also recommended based on the results in this thesis. In this way, the overall impacts from Norwegian bioenergy would be reduced. The high impacts of the thermal, electricity option result in a recommendation of not using biomass for stand-alone electricity production.

Different feedstocks have different properties, which might affect the suitability for different treatment options. This is not investigated in this report. Excluding this, pelletising is advantageous for all the feedstock assessed. To increase the flexibility of bioenergy systems, it is recommended that several materials can be combusted in the same conversion units. For example, because of the storage benefits for TOP and pellets, it is recommended to decrease the storage time of chips and rather utilise chips resources when available in the market. For AP, PMFP and FETP, chips combustion is performing better than both pellets and TOP. For both PMFP and FETP the pellets cases are the least advantageous. Based on the high GWP of TOP materials, it is recommended that torrefied pellets are used to cover the peak load. Also, if a larger scale of biomass export is to be relevant for Norway, TOP is the recommended material for export. If storage time is reduced for chips systems, such value chains might experience higher benefits over both TOP and pellets for GWP. Again, pellet production is highly recommended because of low climate change impacts. For the planned increase in bioenergy towards 2020, forest extraction for energy should be pursued.

Forest residues have the highest impacts of the forest resources for all impact categories assessed. Nutrient recycling in forest has been stated to be an issue if forest residue harvest is too intensive. Assuming that 15 wt.% is left in forest for harvest, and that the majority of what is left is nutrient rich needles, it is assumed that this issue can be eliminated for aboveground forest residues harvest. Arguing that not harvesting forest residue leads to biomass decay and resulting GHG emissions, extraction of this resource is favourable. Clearing of forest land will also lead to somewhat better growth conditions for growing forest (Vennesland et al., 2006). More influential, clearing of forest land implies greater surface albedo effects and therefore also more advantageous forest resource systems. In addition, baling of forest residues results in high impact. Based on these issues, further investigation of forest residues impacts is recommended.

There are possibilities of using carbon negative technologies in Norway through both CCS for biomass combustion, i.e. bio-CCS, and storage of biochar in soil (Regjeringen, 2011). Looking at future scenarios with use of such incentives and technologies would offer valuable information for Norway's bio-future – particularly related to the Government's ambitions of use of biomass and forests as climate incentives (Regjeringen, 2011).

As stated in the introduction there are several studies that have investigated systems with biomass gasification, both with and without CCS. Torrefied biomass offers many advantages for use in gasification plants, which will increase the energy efficiency (Lee, 2009). An increase in energy efficiency will lead to a more efficient system in general, and the environmental burdens could be lowered. Integrating a biomass IGCC with CCS is thought to lower the GWP substantially, and such results would contribute to important information for future, Norwegian bioenergy use.

The co-firing rate of biomass to coal is at present limited because of the differences between the nature of biomass and coal, but torrefaction is an option that can increase this co-firing rate (Bergman et al., 2005). Increasing the co-firing rate would contribute to lowering coal fired power plants' environmental burdens, and this would be particularly interesting for several European countries using coal power to date. Investigating the environmental performance of co-fired coal and torrefied biomass systems in a life cycle perspective, would offer interesting knowledge on a torrefaction system in a broader perspective – particularly if investigating several impact categories in addition to GWP. As stated in the introduction, several studies investigate co-firing of coal and biomass, and looking at a torrefaction based biomass system might offer new, important insight. This would be particularly relevant for a Norwegian biomass export case.

The total Norwegian greenhouse gas emissions was 53,9 million tonnes CO_2-equivalents in 2010 (Regjeringen, 2011). The reference scenario modelled shows a total GWP of 0,58 million tonnes of CO_2-equivalents. Biogenic CO_2 emissions are not accounted for by the Norwegian Government, but comparing the results of the reference scenario to the total Norwegian GHG emissions indicates that the emissions from the modelled system are about 1 % of the total. This indicates a rather low impact from Norwegian bioenergy, mainly based on a comparison where oil production is included though.

7.4 Conclusion

The Norwegian Government has ambitious targets to become carbon neutral by 2030 and reduce the GHG emissions substantially by 2020. This thesis finds considerable climate change impacts from bioenergy compared to conventional treatment of bioenergy systems. This study includes global warming potential for biogenic CO_2 emissions and has strived to model the climate change impact as accurately as possible. In addition to including the impact from biogenic CO_2 emissions, GHG emissions have been included throughout the entire value chains, and surface albedo effects are incorporated for many of the forest resources assessed. The results suggest that the ambitious goal of becoming climate neutral by 2030 cannot be pursued by the use of bioenergy. Bioenergy systems contribute considerably to climate change impact, as biogenic CO_2 emissions are included – which have a radiative forcing in the atmosphere before sequestration. Including albedo effects though, the total global warming potential is reduced substantially with intensive forestry use. The overall findings therefore point to the importance of including both biogenic CO_2 emissions and surface albedo effects.

The bioenergy combustion units investigated in this thesis have an assumed life time of 25 years, which suggest that units built today will be in use beyond 2035. Therefore, when assessing future development of bioenergy, it is important to assess the climate change impact as exact as possible. In a shorter time perspective, Norwegian bioenergy can contribute to reduce GHG emissions towards 2020. At the same time, potential new bioenergy infrastructure units in Norway must be carefully considered as bioenergy has a global warming potential suggesting it cannot be pursued in a market striving to become climate neutral.

On the other hand, traditionally, bioenergy systems are considered carbon neutral. Further investigation of the climate effects of bioenergy systems is therefore essential. At the same time, becoming climate neutral by 2030 might be a too ambitious target for Norway – particularly when investigating the impacts from a life cycle perspective. For Norwegian industry, heat and process steam are important operational inputs. Neither wind, hydro or solar energy sources can contribute to direct steam production. Bioenergy is the only carbon based energy carrier today, and it will be important to include such an energy source in the Norwegian energy system – also related to ambitions regarding use of district heating.

Looking at the large amount of renewable bioenergy resources available, these should be utilised. Biomass decay has been stated to have a climate change impact. In Norway, large amounts of forest resources are available, and the resulting GWP is quite low from forests systems when including surface albedo effects. Extraction is also beneficial to avoid overgrown forests, negatively affecting both cultural landscapes and forest as recreational sites (Vennesland et al., 2006).

This assessment, including and using GWP_{bio} factors, gives a result of 134 grams CO_2-equivalents per kWh from current Norwegian bioenergy use. The GWP is only increasing with about 1.5 % in the modelled alternative scenario, where forest resources are extensively utilised. The results found are relevant for decision makers in Norway aiming at substantially reducing GHG emissions. Awareness of the high GWP of bioenergy systems is important for future developments of the Norwegian energy system.

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9 APPENDICES

This chapter will present all appendices; densities and heating values, softwood/hardwood fractions, harvesting data, biomass expansion factors, transport vectors, life cycle inventories, foreground matrices, Matlab script, and feasible value chains combinations.

9.1 Appendix 1: densities and heating values

This chapter introduces the oven dry densities and the lower heating values on a dry and wet basis. All densities and heating values are calculated based on Table 31 and Table 32 respectively throughout the assessment.

The density depends on the moisture content of the fuel, and can be found from equation (15 at different steps in the value chain. Also the heating values, both on a wet and dry basis, is dependent upon the moisture content, and can be calculated on a wet and dry basis respectively from equation (16 and (17.

Both densities and heating values varies for different types of biomass based fuels and for different species. Fraction for each tree species is given in Table 3 in the theory chapter, and are used to find the overall densities and heating values for the stemwood case.

Oven dry density [kg/m3]	
Norway spruce	*400*
Scots pine	*440*

Birch	*510*
Overall stemwood	428,9 a)
Forest residues	80,0 b)
Baled forest residues	110,0 b)
Energy wood	404,3 c)
Saw residues	149,9 c)
Paper and cardboard waste	141,0 d)
Waste wood	163,0 d)

Table 30: oven dry densities

a) (Belbo and Gjølsjø, 2008)

b) (Hoyne and Thomas, 2001)

c) (Alakangas, 2005)

d) (EPA Victoria, n.d.)

$$\rho = \frac{\rho_d}{1 - MC} \tag{15}$$

MC: moisture content [%]

$W_{ea,d}$ [MJ/kg] (0 % MC)	
Norway spruce	*19,296*
Scots pine	*19,008*
Birch	*19,188*
Overall stemwood	19,18 a)
Forest residues	19,3 b)
Energy wood	19,3 c)
Saw residues	19,0 d)
Paper and cardboard waste	20,8 e)
Wood waste	22,3 f)

Table 31: lower heating value dry basis

a) (Belbo and Gjølsjø, 2008)

b) (Loo and Koppejan, 2007)

c) (Alakangas, 2005)

d) (Wilén et al., 1996)

e) (Phyllis, n.d.)

f) (BIODAT, n.d.)

(16)

$$Wem_{wb} = Wea_d - 0{,}217 * MC$$ (Høibø, 2010)

(17)

$$Wem_{db} = Wea_d - 2{,}45 * \frac{MC}{100 - MC}$$ (Høibø, 2010)

9.2 Appendix 2: harvesting data

Table 33 and Table 34 below present the harvesting inputs applied for stemwood/forest residues and thinning wood respectively (Skog Forsk, 2006). Table 35 presents the forwarding values.

Harvesting, commercial roundwood, with Cable Crane				
Output/FU:	1	m3		
Technosphere inputs:				
Diesel	0,6	litre	0,54	kg
Air Emissions:				
CO_2	1,60	kg		
SO_2	5,04E-05	kg		
Cadmium	5,04E-09	kg		
Copper	8,57E-07	kg		
Chromium	2,52E-08	kg		
Nickel	3,53E-08	kg		
Selenium	5,04E-09	kg		
Zinc	5,04E-07	kg		
Lead	5,54E-14	kg		
Mercury	1,01E-11	kg		
Chromium VI	5,04E-11	kg		

Table 32: harvesting inputs for commercial roundwood (Skog Forsk, 2006).

Harvesting, commercial thinning wood				
Output/FU:	1	m3		
Technosphere inputs:				
Diesel	1,76	litre	1,48	kg/m3
Air Emissions:				
CO_2	4,69	kg		
SO_2	1,48E-04	kg		
Cadmium	1,48E-08	kg		
Copper	2,51E-06	kg		
Chromium	7,39E-08	kg		
Nickel	1,03E-07	kg		
Selenium	1,48E-08	kg		
Zinc	1,48E-06	kg		

Lead	1,63E-13	kg
Mercury	2,96E-11	kg
Chromium	1,48E-10	kg

Table 33: harvesting inputs for commercial thinning wood (Skog Forsk, 2006).

Forwarding, commercial roundwood, from harvest area to forest road				
Output/FU:	1	m3m	1	tkm
Technosphere inputs:				
Diesel	0,00164	litre	1,17	litre
Air Emissions:			1,05	kg
CO2	4,37E-03	kg	3,75	kg
SO2	1,38E-07	kg	1,18E-04	kg
Cadmium	1,38E-11	kg	1,18E-08	kg
Copper	2,34E-09	kg	2,01E-06	kg
Chromium	6,89E-11	kg	5,91E-08	kg
Nickel	9,64E-11	kg	8,27E-08	kg
Selenium	1,38E-11	kg	1,18E-08	kg
Zinc	1,38E-09	kg	1,18E-06	kg
Lead	1,52E-16	kg	1,30E-13	kg
Mercury	2,76E-14	kg	2,36E-11	kg
Chromium VI	1,38E-13	kg	1,18E-10	kg

Table 34: forwarding inputs (Skog Forsk, 2006).

9.3 Appendix 3: BEF

Biomass expansion factors are utilised for mass allocation for stemwood and forest residues. The factors are calculated for 75 % aboveground forest residues with:

- 75 % of available branches
- 25 % of foliage
- Tops: 1,6 % of stem and bark

BEFs of 0,20 and 0, 80 are found for forest residues and stemwood respectively. The forest residue factor is be characterised per m^3 forest residues, and is therefore calculated by 0,78 m^3 stemwood per m^3 forest residues.

9.4 Appendix 4: transport vectors

The transport vectors for the transport distances to pre-treatment site and conversion site respectively are presented below. Chipping and the saw residues direct case have pre-treatment at conversion site, and therefore only have one transport distance.

	trans_feed	**[(km*kg)/kg]**	
1	Wood waste-saw residues TOP	0,00	*Not an option*
2	Wood waste-saw residues pellet	0,00	*Not an option*
3	Wood waste-saw residues direct	0,00	*Not an option*
4	Wood waste-TOP ww	20,00	
5	Wood waste-TOP cw	0,00	*Not an option*
6	wood waste-pellet	20,00	
7	Wood waste-chipping	140,00	
8	P&C waste-saw residues TOP	0,00	*Not an option*
9	P&C waste-saw residues pellet	0,00	*Not an option*
10	P&C waste-saw residues direct	0,00	*Not an option*
11	P&C waste-TOP ww	0,00	*Not an option*
12	P&C waste-TOP cw	0,00	*Not an option*
13	P&C waste-pellet	0,00	*Not an option*
14	P&C waste-chipping	140,00	
15	SR-saw residues TOP	20,00	
16	SR-saw residues pellet	20,00	
17	SR-saw residues direct	140,00	
18	SR-TOP ww	0,00	*Not an option*
19	SR-TOP cw	0,00	*Not an option*
20	SR-pellet	0,00	*Not an option*
21	SR-chipping	0,00	*Not an option*
22	EW- saw residues TOP	0,00	*Not an option*
23	EW- saw residues pellet	0,00	*Not an option*
24	EW- saw residues direct	0,00	*Not an option*
25	EW-TOP ww	0,00	*Not an option*
26	EW-TOP cw	40,00	
27	EW-pellet	40,00	
28	EW-chipping	160,00	
29	FR- saw residues TOP	0,00	*Not an option*
30	FR- saw residues pellet	0,00	*Not an option*
31	FR- saw residues direct	0,00	*Not an option*
32	FR-TOP ww	0,00	*Not an option*
33	FR-TOP cw	40,00	
34	FR-pellet	40,00	

35	FR-chipping	160,00	
36	Stemwood- saw residues TOP	0,00	*Not an option*
37	Stemwood- saw residues pellet	0,00	*Not an option*
38	Stemwood- saw residues direct	0,00	*Not an option*
39	Stemwood-TOP ww	0,00	*Not an option*
40	Stemwood-TOP cw	40,00	
41	Stemwood-pellet	40,00	
42	Stemwood-chipping	160,00	

Table 35: trans_feed vector applied for the transport distance to pre-treatment site.

	trans_treat	**[(kg*km) / MJ]**	
1	Saw residues TOP-steam ww	0,00	*Not an option*
2	Saw residues TOP-steam cw	5,77	
3	Saw residues TOP- DH ww	0,00	*Not an option*
4	Saw residues TOP- DH cw	5,77	
5	Saw residues TOP-th el ww	0,00	*Not an option*
6	Saw residues TOP-th el cw	5,77	
7	Saw residues TOP- CHP heat ww	0,00	*Not an option*
8	Saw residues TOP- CHP heat cw	5,77	
9	Saw residues TOP- CHP el ww	0,00	*Not an option*
10	Saw residues TOP-CHP el cw	5,77	
11	Saw residues pellet-steam ww	0,00	*Not an option*
12	Saw residues pellet-steam cw	7,10	
13	Saw residues pellet- DH ww	0,00	*Not an option*
14	Saw residues pellet- DH cw	7,10	
15	Saw residues pellet-th el ww	0,00	*Not an option*
16	Saw residues pellet-th el cw	7,10	
17	Saw residues pellet- CHP heat ww	0,00	*Not an option*
18	Saw residues pellet- CHP heat cw	7,10	
19	Saw residues pellet- CHP el ww	0,00	*Not an option*
20	Saw residues pellet-CHP el cw	7,10	
21	Saw residues direct-steam ww	0,00	
22	Saw residues direct-steam cw	0,00	
23	Saw residues direct- DH ww	0,00	
24	Saw residues direct- DH cw	0,00	
25	Saw residues direct-th el ww	0,00	
26	Saw residues direct-th el cw	0,00	
27	Saw residues direct- CHP heat ww	0,00	
28	Saw residues direct- CHP heat cw	0,00	
29	Saw residues direct- CHP el ww	0,00	
30	Saw residues direct-CHP el cw	0,00	

31	TOP ww-steam ww	5,77	
32	TOP ww-steam cw	0,00	*Not an option*
33	TOP ww- DH ww	5,77	
34	TOP ww- DH cw	0,00	*Not an option*
35	TOP ww-th el ww	5,77	
36	TOP ww-th el cw	0,00	*Not an option*
37	TOP ww- CHP heat ww	5,77	
38	TOP ww- CHP heat cw	0,00	*Not an option*
39	TOP ww- CHP el ww	5,77	
40	TOP ww-CHP el cw	0,00	*Not an option*
41	TOP cw-steam ww	0,00	*Not an option*
42	TOP cw-steam cw	5,77	
43	TOP cw- DH ww	0,00	*Not an option*
44	TOP cw- DH cw	5,77	
45	TOP cw-th el ww	0,00	*Not an option*
46	TOP cw-th el cw	5,77	
47	TOP cw- CHP heat ww	0,00	*Not an option*
48	TOP cw- CHP heat cw	5,77	
49	TOP cw- CHP el ww	0,00	*Not an option*
50	TOP cw-CHP el cw	5,77	
51	Pellet-steam ww	7,10	
52	Pellet-steam cw	7,10	
53	Pellet- DH ww	7,10	
54	Pellet- DH cw	7,10	
55	Pellet-th el ww	7,10	
56	Pellet-th el cw	7,10	
57	Pellet- CHP heat ww	7,10	
58	Pellet- CHP heat cw	7,10	
59	Pellet- CHP el ww	7,10	
60	Pellet-CHP el cw	7,10	
61	Chipping-steam ww	0,00	
62	Chipping-steam cw	0,00	
63	Chipping- DH ww	0,00	
64	Chipping- DH cw	0,00	
65	Chipping-th el ww	0,00	
66	Chipping-th el cw	0,00	
67	Chipping- CHP heat ww	0,00	
68	Chipping- CHP heat cw	0,00	
69	Chipping- CHP el ww	0,00	
70	Chipping-CHP el cw	0,00	

Table 36: trans_treat vector applied for the transport distance to energy conversion site. The vector is calculated from heating values (wet basis) and transport distances.

9.5 Appendix 5: life cycle inventories

Life cycle inventories for the different process steps and alternatives are presented here.

9.5.1 Feedstock

Stemwood		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
Harvesting softwood		
Industrial wood, Scandinavian softwood, under bark, u=140%, at forest road/NORDEL	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,57E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	2,31E-01	kg
Harvesting hardwood		
Industrial wood, Scandinavian hardwood, under bark, u=80%, at forest road/NORDEL	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,57E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	4,11E-02	kg
Forwarding		
Transport, tractor and trailer/CH	1,00E+00	tkm
Diesel, at regional storage/CH	1,01E+00	kg
Emissions		
Stressor name	**Value**	***Unit***
Harvesting softwood		
Carbon dioxide, fossil/ air/ low population density	1,20E+00	kg
Lead/ air/ low population density	-2,13E-05	kg
Sulfur dioxide/ air/ low population density	-1,47E-04	kg
Harvesting hardwood		
Carbon dioxide, fossil/ air/ low population density	9,46E-01	kg
Lead/ air/ low population density	-3,45E-05	kg
Sulfur dioxide/ air/ low population density	-2,69E-04	kg
Storage in forest		
Carbon dioxide, biogenic/ air/ low population density	1,01E-02	kg
Forwarding		
Carbon dioxide, fossil/ air/ low population density	3,61E+00	kg
Sulfur dioxide/ air/ low population density	7,42E-05	kg
Cadmium/ air/ low population density	1,14E-08	kg
Copper/ air/ low population density	1,93E-06	kg

Chromium/ air/ low population density	5,69E-08	kg
Nickel/ air/ low population density	7,97E-08	kg
Selenium/ air/ low population density	1,14E-08	kg
Zinc/ air/ low population density	1,14E-06	kg
Lead/ air/ low population density	1,30E-13	kg
Mercury/ air/ low population density	2,36E-11	kg
Chromium VI/ air/ low population density	1,18E-10	kg
Storage at forest road		
Carbon dioxide, biogenic/ air/ low population density	0,00E+00	kg

Table 37: stemwood inventory.

Forest residues		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
Harvesting softwood		
Industrial wood, Scandinavian softwood, under bark, u=140%, at forest road/NORDEL	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,57E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	2,31E-01	kg
Harvesting hardwood		
Industrial wood, Scandinavian hardwood, under bark, u=80%, at forest road/NORDEL	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,57E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	4,11E-02	kg
Baling		
Baling/ CH	7,14E-01	m3
Forwarding		
Transport, tractor and trailer/CH	1,00E+00	tkm
Diesel, at regional storage/CH	1,01E+00	kg
Emissions		
Stressor name	**Value**	***Unit***
Harvesting softwood		
Carbon dioxide, fossil/ air/ low population density	1,20E+00	kg
Lead/ air/ low population density	-2,13E-05	kg
Sulfur dioxide/ air/ low population density	-1,47E-04	kg
Harvesting hardwood		
Carbon dioxide, fossil/ air/ low population density	9,46E-01	kg
Lead/ air/ low population density	-3,45E-05	kg
Sulfur dioxide/ air/ low population density	-2,69E-04	kg
Baling		
Carbon dioxide, biogenic/ air/ low population density	1,42E-05	kg

Forwarding		
Carbon dioxide, fossil/ air/ low population density	3,61E+00	kg
Sulfur dioxide/ air/ low population density	7,42E-05	kg
Cadmium/ air/ low population density	1,14E-08	kg
Copper/ air/ low population density	1,93E-06	kg
Chromium/ air/ low population density	5,69E-08	kg
Nickel/ air/ low population density	7,97E-08	kg
Selenium/ air/ low population density	1,14E-08	kg
Zinc/ air/ low population density	1,14E-06	kg
Lead/ air/ low population density	1,30E-13	kg
Mercury/ air/ low population density	2,36E-11	kg
Chromium VI/ air/ low population density	1,18E-10	kg
Storage at forest road		
Carbon dioxide, biogenic/ air/ low population density	1,01E-02	kg

Table 38: forest residue inventory.

Energy wood		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
Harvesting softwood		
Residual wood, softwood, under bark, u=140%, at forest road/ RER	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,37E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	1,25E+00	kg
Harvesting hardwood		
Residual wood, hardwood, under bark, u=80%, at forest road/ RER	1,00E+00	m3
Transport, lorry 3.5-16t, fleet average/RER	-3,37E-01	tkm
Petrol, two-stroke blend, at regional storage/RER	1,36E+00	kg
Forwarding		
Transport, tractor and trailer/CH	1,00E+00	tkm
Diesel, at regional storage/CH	1,01E+00	kg
Emissions		
Stressor name	**Value**	***Unit***
Harvesting softwood		
Carbon dioxide, fossil/ air/ low population density	4,38E+00	kg
Lead/ air/ low population density	-1,62E-05	kg
Sulfur dioxide/ air/ low population density	-1,67E-06	kg
Harvesting hardwood		
Carbon dioxide, fossil/ air/ low population density	4,53E+00	kg
Lead/ air/ low population density	-8,37E-06	kg
Sulfur dioxide/ air/ low population density	7,03E-05	kg
Storage in forest		
Carbon dioxide, biogenic/ air/ low population density	4,36E-03	kg
Forwarding		

Carbon dioxide, fossil/ air/ low population density	3,61E+00	kg
Sulfur dioxide/ air/ low population density	7,42E-05	kg
Cadmium/ air/ low population density	1,14E-08	kg
Copper/ air/ low population density	1,93E-06	kg
Chromium/ air/ low population density	5,69E-08	kg
Nickel/ air/ low population density	7,97E-08	kg
Selenium/ air/ low population density	1,14E-08	kg
Zinc/ air/ low population density	1,14E-06	kg
Lead/ air/ low population density	1,30E-13	kg
Mercury/ air/ low population density	2,36E-11	kg
Chromium VI/ air/ low population density	1,18E-10	kg
Storage at forest road		
Carbon dioxide, biogenic/ air/ low population density	0,00E+00	kg

Table 39: energy wood inventory.

Saw residues		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
Collection softwood		
Sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant/NORDEL	1,18E-01	m3
Chips, Scandinavian softwood (plant-debarked), u=70%, at plant/ NORDEL	8,82E-01	m3
Collection hardwood		
Sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant/NORDEL	1,18E-01	m3
Round wood, Scandinavian softwood, under bark, u=70% at forest road/ NORDEL	-7,57E-02	m3
round wood, hardwood, under bark, u=70%, at forest road/ RER	7,57E-02	m3
Softwood, allocation, correction, 2/ RER	-9,24E-01	m3
Hardwood, allocation correction, 2/ RER	9,24E-01	m3
Chips, Scandinavian softwood (plant-debarked), u=70%, at plant/ NORDEL	8,82E-01	m3

Table 40: saw residue inventory.

Collection P&C waste		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
electricity, high voltage, production NORDEL, at grid/ NORDEL	6,00E-05	kWh
electricity, medium voltage, production NORDEL, at grid/ NORDEL	1,38E-05	kWh
electricity, low voltage, production NORDEL, at grid/ NORDEL	9,22E-05	kWh
alkyd paint, white, 60% in H2O, at plant/ RER	1,21E-07	kg
alkyd paint, white, 60% in solvent, at plant/ RER	1,21E-07	kg
aluminium, primary, at plant/ RER/	2,15E-06	kg
concrete block, at plant/ DE	1,93E-04	kg
gravel, unspecified, at mine/ CH	2,18E-03	kg
glass cullets, mixed glass, for CRT glass production, at plant/ GLO	2,71E-07	kg

synthetic rubber, at plant/ RER	2,89E-06	kg
sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/ NORDEL	2,87E-09	m3
copper, at regional storage/ RER	5,87E-07	kg
polyethylene, LDPE, granulate, at plant/ RER	9,87E-07	kg
polypropylene, granulate, at plant/ RER	1,35E-06	kg
steel, low-alloyed, at plant/ RER	4,02E-05	kg
transport, lorry >28t, fleet average/ CH	1,78E-05	tkm
transport, passenger car, diesel, fleet average/ RER	9,95E-06	pkm
excavation, skid-steer loader/ RER	2,24E-06	m3
diesel, burned in building machine/ GLO	5,14E-04	MJ
bitumen, at refinery/ RER	2,90E-05	kg
heat, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW/ RER	2,27E-04	MJ
heat, at hard coal industrial furnace 1-10MW/ RER	3,34E-05	MJ
disposal, inert waste, 5% water, to inert material landfill/ CH	6,55E-05	kg
disposal, asphalt, 0.1% water, to sanitary landfill/ CH	5,80E-04	kg
disposal, plastics, mixture, 15.3% water, to sanitary landfill/ CH	7,26E-06	kg
Emissions		
Stressor name	**Value**	***Unit***
Water, unspecified natural origin/ resource/ in water	1,19E-06	kg
Occupation, arable/ resource/ land	3,84E-05	m2a
Occupation, industrial area/ resource/ land	3,84E-05	m2a
Occupation, pasture and meadow/ resource/ land	3,84E-05	m2a
Methane, fossil/ air/ unspecified	5,80E-10	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	5,18E-05	kg
Heat, waste/ air/ unspecified	5,97E-04	MJ
Chloride/ water/ unspecified	1,24E-05	kg

Table 41: paper and cardboard waste inventory.

Collection wood waste		
Technosphere inputs		
Background Process Name	***Value***	***Unit***
electricity, high voltage, production NORDEL, at grid/ NORDEL	6,00E-05	kWh
electricity, medium voltage, production NORDEL, at grid/ NORDEL	1,38E-05	kWh
electricity, low voltage, production NORDEL, at grid/ NORDEL	9,22E-05	kWh
alkyd paint, white, 60% in H2O, at plant/ RER	1,21E-07	kg
alkyd paint, white, 60% in solvent, at plant/ RER	1,21E-07	kg
aluminium, primary, at plant/ RER/	2,15E-06	kg
concrete block, at plant/ DE	1,93E-04	kg
gravel, unspecified, at mine/ CH	2,18E-03	kg
glass cullets, mixed glass, for CRT glass production, at plant/ GLO	2,71E-07	kg

synthetic rubber, at plant/ RER	2,89E-06	kg
sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/ NORDEL	2,87E-09	m3
copper, at regional storage/ RER	5,87E-07	kg
polyethylene, LDPE, granulate, at plant/ RER	9,87E-07	kg
polypropylene, granulate, at plant/ RER	1,35E-06	kg
steel, low-alloyed, at plant/ RER	4,02E-05	kg
transport, lorry >28t, fleet average/ CH	1,78E-05	tkm
transport, passenger car, diesel, fleet average/ RER	9,95E-06	pkm
excavation, skid-steer loader/ RER	2,24E-06	m3
diesel, burned in building machine/ GLO	5,14E-04	MJ
bitumen, at refinery/ RER	2,90E-05	kg
heat, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW/ RER	2,27E-04	MJ
heat, at hard coal industrial furnace 1-10MW/ RER	3,34E-05	MJ
disposal, inert waste, 5% water, to inert material landfill/ CH	6,55E-05	kg
disposal, asphalt, 0.1% water, to sanitary landfill/ CH	5,80E-04	kg
disposal, plastics, mixture, 15.3% water, to sanitary landfill/ CH	7,26E-06	kg
Emissions		
Stressor name	**Value**	***Unit***
Water, unspecified natural origin/ resource/ in water	1,19E-06	kg
Occupation, arable/ resource/ land	3,84E-05	m2a
Occupation, industrial area/ resource/ land	3,84E-05	m2a
Occupation, pasture and meadow/ resource/ land	3,84E-05	m2a
Methane, fossil/ air/ unspecified	5,80E-10	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	5,18E-05	kg
Heat, waste/ air/ unspecified	5,97E-04	MJ
Chloride/ water/ unspecified	1,24E-05	kg

Table 42: construction and demolition wood waste inventory.

9.5.2 Transport to pre-treatment site

Technosphere inputs		
Background Process Name	**Value**	***Unit***
transport, lorry >16t, fleet average/ RER	1,00E+00	tkm

Table 43: inventory for transport to pre-treatment site.

9.5.3 Treatment

Chipping		
Technosphere inputs		
Background Process Name	**Value**	***Unit***

Chipping		
Chopper, stationary, electric/RER/I U	9,44E-06	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	23,29	kWh
Lubricating oil, at plant/RER U	3,63E-04	kg
Steel, low-alloyed, at plant/RER U	7,27E-04	kg
Emissions		
Stressor name	**Value**	***Unit***
Chipping		
Carbon dioxide, biogenic/ air/ unspecified	6,54E+00	kg
Heat, waste	4,95E-02	MJ
Chips storage		
Dinitrogen monoxide/ air/ unspecified	2,29E-05	kg
Methane, biogenic/ air/ unspecified	1,15E-03	kg
Carbon dioxide, biogenic/ air/ unspecified	5,21E-03	kg

Table 44: chipping inventory

Pelletising		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Chipping		
Chopper, stationary, electric/RER/I U	9,44E-06	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	23,29	kWh
Lubricating oil, at plant/RER U	3,63E-04	kg
Steel, low-alloyed, at plant/RER U	7,27E-04	kg
Pre-treatment and drying		
industrial furnace, coal, 1-10 MW/ RER/ unit	1,65E-05	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	1,27E+01	kWh
Pelletising		
Wood pellet manufacturing, infrastructure/RER/I U	1,74E-05	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	3,36	kWh
Emissions		
Stressor name	**Value**	***Unit***
Chipping		
Carbon dioxide, biogenic/ air/ unspecified	6,54E+00	kg
Heat, waste	4,95E-02	MJ
Chips storage		
Dinitrogen monoxide/ air/ high population density	7,64E-06	kg
Methane, biogenic/ air/ high population density	3,82E-04	kg
Carbon dioxide, biogenic/ air/ unspecified	4,60E-03	kg
Pelletising		
Heat, waste	591	MJ

Table 45: pelletising inventory

TOP cw		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Chipping		
Chopper, stationary, electric/RER/I U	9,44E-06	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	23,29	kWh
Lubricating oil, at plant/RER U	3,63E-04	kg
Steel, low-alloyed, at plant/RER U	7,27E-04	kg
TOP infrastructure		
industrial furnace, coal, 1-10 MW/ RER/ unit	2,00E+00	p
Wood pellet manufacturing, infrastructure/RER/I U	1,00E+00	p
TOP ash to landfilling		
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U	1,00E+00	kg
TOP		
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	1,99E-02	kWh
Emissions		
Stressor name	**Value**	***Unit***
Chipping		
Carbon dioxide, biogenic/ air/ unspecified	6,54E+00	kg
Heat, waste	4,95E-02	MJ
Chips storage		
Dinitrogen monoxide/ air/ high population density	7,64E-06	kg
Methane, biogenic/ air/ high population density	3,82E-04	kg
Carbon dioxide, biogenic/ air/ unspecified	4,55E-03	kg
TOP ash to landfilling		
Aluminium/ air/ high population density	1,36E-07	kg
Aluminium/ air/ low population density	2,08E-08	kg
Aluminium/ water/ groundwater	3,32E-02	kg
Aluminium/ water/ river	4,98E-06	kg
Arsenic, ion/ water/ groundwater	-1,86E-06	kg
Arsenic, ion/ water/ river	-1,48E-08	kg
Arsenic/ air/ high population density	-4,72E-12	kg
Arsenic/ air/ low population density	-2,35E-10	kg
BOD5, Biological Oxygen Demand/ water/ groundwater	1,01E-01	kg
BOD5, Biological Oxygen Demand/ water/ river	4,65E-04	kg
Cadmium, ion/ water/ groundwater	-1,21E-05	kg
Cadmium, ion/ water/ river	-5,43E-08	kg
Cadmium/ air/ high population density	-2,93E-12	kg
Cadmium/ air/ low population density	-7,13E-10	kg
Calcium, ion/ water/ groundwater	-2,56E-03	kg

Calcium, ion/ water/ river	-1,51E-05	kg
Calcium/ air/ high population density	-2,74E-09	kg
Calcium/ air/ low population density	-4,19E-09	kg
Carbon dioxide, biogenic/ air/ high population density	1,45E-03	kg
Carbon dioxide, biogenic/ air/ low population density	4,33E-02	kg
Chloride/ water/ groundwater	-2,69E-03	kg
Chloride/ water/ river	-5,01E-04	kg
Chromium VI/ water/ groundwater	7,50E-04	kg
Chromium VI/ water/ river	4,92E-05	kg
Chromium, ion/ water/ river	1,47E-07	kg
Chromium/ air/ high population density	3,42E-12	kg
Chromium/ air/ low population density	2,35E-08	kg
Cobalt/ air/ high population density	-4,06E-16	kg
Cobalt/ air/ low population density	-6,50E-12	kg
Cobalt/ water/ groundwater	-1,60E-06	kg
Cobalt/ water/ river	-1,32E-08	kg
Copper, ion/ water/ groundwater	9,01E-04	kg
Copper, ion/ water/ river	5,75E-08	kg
Copper/ air/ high population density	1,20E-12	kg
Copper/ air/ low population density	6,30E-11	kg
Iron, ion/ water/ groundwater	3,36E-02	kg
Iron, ion/ water/ river	1,63E-04	kg
Iron/ air/ high population density	7,92E-08	kg
Iron/ air/ low population density	7,98E-08	kg
Lead/ air/ high population density	1,66E-13	kg
Lead/ air/ low population density	1,67E-12	kg
Lead/ water/ groundwater	1,71E-05	kg
Lead/ water/ river	5,51E-10	kg
Magnesium/ air/ high population density	3,61E-08	kg
Magnesium/ air/ low population density	6,69E-08	kg
Magnesium/ water/ groundwater	8,41E-03	kg
Magnesium/ water/ river	2,41E-04	kg
Manganese/ air/ high population density	-6,11E-13	kg
Manganese/ air/ low population density	-5,71E-08	kg
Manganese/ water/ groundwater	-3,77E-03	kg
Manganese/ water/ river	-1,16E-04	kg
Molybdenum/ air/ high population density	2,43E-11	kg
Molybdenum/ air/ low population density	6,17E-12	kg
Molybdenum/ water/ groundwater	1,85E-06	kg
Molybdenum/ water/ river	1,46E-08	kg
Nickel, ion/ water/ groundwater	3,51E-05	kg
Nickel, ion/ water/ river	6,20E-08	kg
Nickel/ air/ high population density	1,74E-15	kg
Nickel/ air/ low population density	2,55E-11	kg

Phosphate/ water/ groundwater	1,28E-02	kg
Phosphate/ water/ river	1,85E-03	kg
Phosphorus/ air/ high population density	-2,62E-05	kg
Potassium, ion/ water/ groundwater	-1,79E-04	kg
Potassium, ion/ water/ river	-6,79E-06	kg
Potassium/ air/ low population density	-1,70E-09	kg
Silicon/ air/ high population density	6,53E-05	kg
Silicon/ air/ low population density	7,45E-06	kg
Silicon/ water/ groundwater	2,30E-01	kg
Silicon/ water/ river	1,79E-03	kg
Sulfate/ water/ groundwater	-4,14E-03	kg
Sulfate/ water/ river	-1,05E-04	kg
Titanium, ion/ water/ groundwater	-1,08E-03	kg
Titanium, ion/ water/ river	-1,75E-06	kg
Titanium/ air/ high population density	-1,70E-09	kg
Titanium/ air/ low population density	-8,64E-10	kg
TOC, Total Organic Carbon/ water/ groundwater	4,26E-03	kg
TOC, Total Organic Carbon/ water/ river	4,07E-06	kg
Vanadium, ion/ water/ groundwater	2,13E-05	kg
Vanadium, ion/ water/ river	1,96E-07	kg
Vanadium/ air/ high population density	1,90E-11	kg
Vanadium/ air/ low population density	9,63E-11	kg
Zinc, ion/ water/ groundwater	-9,31E-04	kg
Zinc, ion/ water/ river	-8,29E-07	kg
Zinc/ air/ high population density/ air/ high population density	-3,02E-11	kg
Zinc/ air/ low population density	-5,94E-10	kg
Sodium, ion/ water/ unspecified	9,43E-03	kg
Barium/ water/ unspecified	7,97E-04	kg
TOP		
Heat, waste/ air/ unspecified	7,39E-01	MJ
Carbon dioxide, biogenic/ air/ unspecified	2,69E-01	kg
Carbon monoxide, biogenic/ air/ unspecified	8,63E-04	kg
Methane, biogenic/ air/ unspecified	1,34E-04	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	1,67E-05	kg
Nitrogen oxides/ air/ unspecified	4,07E-04	kg
Dinitrogen monoxide/ air/ unspecified	7,68E-06	kg
Sulfur dioxide/ air/ unspecified	7,30E-06	kg
PAH, polycyclic aromatic hydrocarbons/ air/ unspecified	2,05E-09	kg
Particulates, < 2.5 um/ air/ unspecified	1,76E-05	kg
Particulates, > 10 um/ air/ unspecified	2,08E-05	kg
Arsenic/ air/ unspecified	4,46E-10	kg
Cadmium/ air/ unspecified	7,65E-10	kg
Cobalt/ air/ unspecified	8,45E-10	kg

Chromium/ air/ unspecified	1,11E-10	kg
Copper/ air/ unspecified	1,73E-10	kg
Mercury/ air/ unspecified	1,68E-09	kg
Manganese/ air/ unspecified	3,07E-11	kg
Nickel/ air/ unspecified	5,38E-11	kg
Lead/ air/ unspecified	8,45E-11	kg
Antimony/ air/ unspecified	1,73E-10	kg
Selenium/ air/ unspecified	6,91E-10	kg
Thallium/ air/ unspecified	6,91E-10	kg
Vanadium/ air/ unspecified	1,73E-10	kg
Zinc/ air/ unspecified	6,50E-09	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2,96E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air/ unspecified	6,95E-14	kg
Hydrocarbons, aromatic/ air/ unspecified	1,53E-08	kg
Formaldehyde/ air/ unspecified	5,76E-06	kg

Table 46: TOP clean wood inventory

TOP ww		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Chipping		
Chopper, stationary, electric/RER/I U	9,44E-06	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	2,33E+01	kWh
Lubricating oil, at plant/RER U	3,63E-04	kg
Steel, low-alloyed, at plant/RER U	7,27E-04	kg
TOP infrastructure		
industrial furnace, coal, 1-10 MW/ RER/ unit	2,00E+00	p
Wood pellet manufacturing, infrastructure/RER/I U	1,00E+00	p
TOP ash to landfilling		
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U	1,00E+00	kg
TOP		
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	1,99E-02	kWh
Emissions		
Stressor name	**Value**	***Unit***
Chipping		
Carbon dioxide, biogenic/ air/ unspecified	6,54E+00	kg
Heat, waste	4,95E-02	MJ
Chips storage		
Dinitrogen monoxide/ air/ high population density	7,64E-06	kg
Methane, biogenic/ air/ high population density	3,82E-04	kg
Carbon dioxide, biogenic/ air/ unspecified	4,55E-03	kg
TOP ash to landfilling		

Aluminium/ air/ high population density	3,82E-07	kg
Aluminium/ air/ low population density	5,84E-08	kg
Aluminium/ water/ groundwater	9,34E-02	kg
Aluminium/ water/ river	1,40E-05	kg
Arsenic, ion/ water/ groundwater	-1,86E-06	kg
Arsenic, ion/ water/ river	-1,48E-08	kg
Arsenic/ air/ high population density	-4,72E-12	kg
Arsenic/ air/ low population density	-2,35E-10	kg
BOD5, Biological Oxygen Demand/ water/ groundwater	1,01E-01	kg
BOD5, Biological Oxygen Demand/ water/ river	4,65E-04	kg
Cadmium, ion/ water/ groundwater	-1,21E-05	kg
Cadmium, ion/ water/ river	-5,43E-08	kg
Cadmium/ air/ high population density	-2,93E-12	kg
Cadmium/ air/ low population density	-7,13E-10	kg
Calcium, ion/ water/ groundwater	-3,79E-02	kg
Calcium, ion/ water/ river	-2,24E-04	kg
Calcium/ air/ high population density	-4,06E-08	kg
Calcium/ air/ low population density	-6,21E-08	kg
Carbon dioxide, biogenic/ air/ high population density	1,45E-03	kg
Carbon dioxide, biogenic/ air/ low population density	4,33E-02	kg
Chloride/ water/ groundwater	-2,69E-03	kg
Chloride/ water/ river	-5,01E-04	kg
Chromium VI/ water/ groundwater	5,14E-04	kg
Chromium VI/ water/ river	3,37E-05	kg
Chromium, ion/ water/ river	1,01E-07	kg
Chromium/ air/ high population density	2,35E-12	kg
Chromium/ air/ low population density	1,61E-08	kg
Cobalt/ air/ high population density	-4,06E-16	kg
Cobalt/ air/ low population density	-6,50E-12	kg
Cobalt/ water/ groundwater	-1,60E-06	kg
Cobalt/ water/ river	-1,32E-08	kg
Copper, ion/ water/ groundwater	4,39E-03	kg
Copper, ion/ water/ river	2,80E-07	kg
Copper/ air/ high population density	5,88E-12	kg
Copper/ air/ low population density	3,07E-10	kg
Iron, ion/ water/ groundwater	5,12E-02	kg
Iron, ion/ water/ river	2,48E-04	kg
Iron/ air/ high population density	1,21E-07	kg
Iron/ air/ low population density	1,22E-07	kg
Lead/ air/ high population density	4,30E-12	kg
Lead/ air/ low population density	4,33E-11	kg
Lead/ water/ groundwater	4,41E-04	kg
Lead/ water/ river	1,43E-08	kg
Magnesium/ air/ high population density	8,27E-09	kg

Magnesium/ air/ low population density	1,53E-08	kg
Magnesium/ water/ groundwater	1,93E-03	kg
Magnesium/ water/ river	5,52E-05	kg
Manganese/ air/ high population density	-6,11E-13	kg
Manganese/ air/ low population density	-5,71E-08	kg
Manganese/ water/ groundwater	-3,77E-03	kg
Manganese/ water/ river	-1,16E-04	kg
Molybdenum/ air/ high population density	2,43E-11	kg
Molybdenum/ air/ low population density	6,17E-12	kg
Molybdenum/ water/ groundwater	1,85E-06	kg
Molybdenum/ water/ river	1,46E-08	kg
Nickel, ion/ water/ groundwater	7,47E-05	kg
Nickel, ion/ water/ river	1,32E-07	kg
Nickel/ air/ high population density	3,70E-15	kg
Nickel/ air/ low population density	5,43E-11	kg
Phosphate/ water/ groundwater	1,08E-02	kg
Phosphate/ water/ river	1,56E-03	kg
Phosphorus/ air/ high population density	2,81E-06	kg
Potassium, ion/ water/ groundwater	-3,14E-02	kg
Potassium, ion/ water/ river	-1,19E-03	kg
Potassium/ air/ low population density	-2,98E-07	kg
Silicon/ air/ high population density	6,13E-05	kg
Silicon/ air/ low population density	7,00E-06	kg
Silicon/ water/ groundwater	2,16E-01	kg
Silicon/ water/ river	1,68E-03	kg
Sulfate/ water/ groundwater	3,64E-03	kg
Sulfate/ water/ river	9,21E-05	kg
Titanium, ion/ water/ groundwater	-1,08E-03	kg
Titanium, ion/ water/ river	-1,75E-06	kg
Titanium/ air/ high population density	-1,70E-09	kg
Titanium/ air/ low population density	-8,64E-10	kg
TOC, Total Organic Carbon/ water/ groundwater	-2,42E-03	kg
TOC, Total Organic Carbon/ water/ river	-2,31E-06	kg
Vanadium, ion/ water/ groundwater	2,13E-05	kg
Vanadium, ion/ water/ river	1,96E-07	kg
Vanadium/ air/ high population density	1,90E-11	kg
Vanadium/ air/ low population density	9,63E-11	kg
Zinc, ion/ water/ groundwater	3,48E-04	kg
Zinc, ion/ water/ river	3,10E-07	kg
Zinc/ air/ high population density/ air/ high population density	1,13E-11	kg
Zinc/ air/ low population density	2,22E-10	kg
Sodium, ion/ water/ unspecified	1,02E-02	kg
Barium/ water/ unspecified	7,97E-04	kg
TOP		

Heat, waste/ air/ unspecified	7,39E-01	MJ
Carbon dioxide, biogenic/ air/ unspecified	2,69E-01	kg
Carbon monoxide, biogenic/ air/ unspecified	8,63E-04	kg
Methane, biogenic/ air/ unspecified	1,54E-04	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	1,67E-05	kg
Nitrogen oxides/ air/ unspecified	4,07E-04	kg
Dinitrogen monoxide/ air/ unspecified	1,54E-05	kg
Sulfur dioxide/ air/ unspecified	7,30E-06	kg
PAH, polycyclic aromatic hydrocarbons/ air/ unspecified	2,05E-09	kg
Particulates, < 2.5 um/ air/ unspecified	1,76E-05	kg
Particulates, > 10 um/ air/ unspecified	2,08E-05	kg
Arsenic/ air/ unspecified	4,46E-10	kg
Cadmium/ air/ unspecified	7,65E-10	kg
Cobalt/ air/ unspecified	8,45E-10	kg
Chromium/ air/ unspecified	1,11E-10	kg
Copper/ air/ unspecified	1,73E-10	kg
Mercury/ air/ unspecified	1,68E-09	kg
Manganese/ air/ unspecified	3,07E-11	kg
Nickel/ air/ unspecified	5,38E-11	kg
Lead/ air/ unspecified	8,45E-11	kg
Antimony/ air/ unspecified	1,73E-10	kg
Selenium/ air/ unspecified	6,91E-10	kg
Thallium/ air/ unspecified	6,91E-10	kg
Vanadium/ air/ unspecified	1,73E-10	kg
Zinc/ air/ unspecified	6,50E-09	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2,96E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air/ unspecified	6,95E-14	kg
Hydrocarbons, aromatic/ air/ unspecified	1,53E-08	kg
Formaldehyde/ air/ unspecified	5,76E-06	kg

Table 47: TOP waste wood inventory

Saw residues direct		
Emissions		
Stressor name	**Value**	***Unit***
Saw residues storage		
Carbon dioxide, biogenic/ air/ unspecified	5,58E-03	kg
Dinitrogen monoxide/ air/ unspecified	7,64E-06	kg
Methane, biogenic/ air/ unspecified	3,82E-04	kg

Table 48: saw residues direct

Pelletising saw residues
Technosphere inputs

Background Process Name	**Value**	***Unit***
Pre-treatment and drying		
industrial furnace, coal, 1-10 MW/ RER/ unit	1,65E-05	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	1,27E+01	kWh
Pelletising		
Wood pellet manufacturing, infrastructure/RER/I U	1,65E-05	p
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	2,53	kWh
Emissions		
Stressor name	**Value**	***Unit***
Saw residues storage		
Carbon dioxide, biogenic/ air/ unspecified	6,33E-03	kg
Dinitrogen monoxide/ air/ unspecified	2,29E-05	kg
Methane, biogenic/ air/ unspecified	1,15E-03	kg
Pelletising		
Heat, waste	591	MJ

Table 49: pelletising saw residues inventory

TOP saw residues		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
TOP infrastructure		
industrial furnace, coal, 1-10 MW/ RER/ unit	2,00E+00	p
Wood pellet manufacturing, infrastructure/RER/I U	1,00E+00	p
TOP ash to landfilling		
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U	1,00E+00	kg
TOP		
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ kWh	1,99E-02	kWh
Emissions		
Stressor name	**Value**	***Unit***
Saw residues storage		
Carbon dioxide, biogenic/ air/ unspecified	5,58E-03	kg
Dinitrogen monoxide/ air/ unspecified	7,64E-06	kg
Methane, biogenic/ air/ unspecified	3,82E-04	kg
TOP ash to landfilling		
Aluminium/ air/ high population density	1,36E-07	kg
Aluminium/ air/ low population density	2,08E-08	kg
Aluminium/ water/ groundwater	3,32E-02	kg
Aluminium/ water/ river	4,98E-06	kg
Arsenic, ion/ water/ groundwater	-1,86E-06	kg
Arsenic, ion/ water/ river	-1,48E-08	kg
Arsenic/ air/ high population density	-4,72E-12	kg
Arsenic/ air/ low population density	-2,35E-10	kg

BOD5, Biological Oxygen Demand/ water/ groundwater	1,01E-01	kg
BOD5, Biological Oxygen Demand/ water/ river	4,65E-04	kg
Cadmium, ion/ water/ groundwater	-1,21E-05	kg
Cadmium, ion/ water/ river	-5,43E-08	kg
Cadmium/ air/ high population density	-2,93E-12	kg
Cadmium/ air/ low population density	-7,13E-10	kg
Calcium, ion/ water/ groundwater	-2,56E-03	kg
Calcium, ion/ water/ river	-1,51E-05	kg
Calcium/ air/ high population density	-2,74E-09	kg
Calcium/ air/ low population density	-4,19E-09	kg
Carbon dioxide, biogenic/ air/ high population density	1,45E-03	kg
Carbon dioxide, biogenic/ air/ low population density	4,33E-02	kg
Chloride/ water/ groundwater	-2,69E-03	kg
Chloride/ water/ river	-5,01E-04	kg
Chromium VI/ water/ groundwater	7,50E-04	kg
Chromium VI/ water/ river	4,92E-05	kg
Chromium, ion/ water/ river	1,47E-07	kg
Chromium/ air/ high population density	3,42E-12	kg
Chromium/ air/ low population density	2,35E-08	kg
Cobalt/ air/ high population density	-4,06E-16	kg
Cobalt/ air/ low population density	-6,50E-12	kg
Cobalt/ water/ groundwater	-1,60E-06	kg
Cobalt/ water/ river	-1,32E-08	kg
Copper, ion/ water/ groundwater	9,01E-04	kg
Copper, ion/ water/ river	5,75E-08	kg
Copper/ air/ high population density	1,20E-12	kg
Copper/ air/ low population density	6,30E-11	kg
Iron, ion/ water/ groundwater	3,36E-02	kg
Iron, ion/ water/ river	1,63E-04	kg
Iron/ air/ high population density	7,92E-08	kg
Iron/ air/ low population density	7,98E-08	kg
Lead/ air/ high population density	1,66E-13	kg
Lead/ air/ low population density	1,67E-12	kg
Lead/ water/ groundwater	1,71E-05	kg
Lead/ water/ river	5,51E-10	kg
Magnesium/ air/ high population density	3,61E-08	kg
Magnesium/ air/ low population density	6,69E-08	kg
Magnesium/ water/ groundwater	8,41E-03	kg
Magnesium/ water/ river	2,41E-04	kg
Manganese/ air/ high population density	-6,11E-13	kg
Manganese/ air/ low population density	-5,71E-08	kg
Manganese/ water/ groundwater	-3,77E-03	kg
Manganese/ water/ river	-1,16E-04	kg
Molybdenum/ air/ high population density	2,43E-11	kg

Molybdenum/ air/ low population density	6,17E-12	kg
Molybdenum/ water/ groundwater	1,85E-06	kg
Molybdenum/ water/ river	1,46E-08	kg
Nickel, ion/ water/ groundwater	3,51E-05	kg
Nickel, ion/ water/ river	6,20E-08	kg
Nickel/ air/ high population density	1,74E-15	kg
Nickel/ air/ low population density	2,55E-11	kg
Phosphate/ water/ groundwater	1,28E-02	kg
Phosphate/ water/ river	1,85E-03	kg
Phosphorus/ air/ high population density	-2,62E-05	kg
Potassium, ion/ water/ groundwater	-1,79E-04	kg
Potassium, ion/ water/ river	-6,79E-06	kg
Potassium/ air/ low population density	-1,70E-09	kg
Silicon/ air/ high population density	6,53E-05	kg
Silicon/ air/ low population density	7,45E-06	kg
Silicon/ water/ groundwater	2,30E-01	kg
Silicon/ water/ river	1,79E-03	kg
Sulfate/ water/ groundwater	-4,14E-03	kg
Sulfate/ water/ river	-1,05E-04	kg
Titanium, ion/ water/ groundwater	-1,08E-03	kg
Titanium, ion/ water/ river	-1,75E-06	kg
Titanium/ air/ high population density	-1,70E-09	kg
Titanium/ air/ low population density	-8,64E-10	kg
TOC, Total Organic Carbon/ water/ groundwater	4,26E-03	kg
TOC, Total Organic Carbon/ water/ river	4,07E-06	kg
Vanadium, ion/ water/ groundwater	2,13E-05	kg
Vanadium, ion/ water/ river	1,96E-07	kg
Vanadium/ air/ high population density	1,90E-11	kg
Vanadium/ air/ low population density	9,63E-11	kg
Zinc, ion/ water/ groundwater	-9,31E-04	kg
Zinc, ion/ water/ river	-8,29E-07	kg
Zinc/ air/ high population density/ air/ high population density	-3,02E-11	kg
Zinc/ air/ low population density	-5,94E-10	kg
Sodium, ion/ water/ unspecified	9,43E-03	kg
Barium/ water/ unspecified	7,97E-04	kg
TOP		
Heat, waste/ air/ unspecified	7,39E-01	MJ
Carbon dioxide, biogenic/ air/ unspecified	2,69E-01	kg
Carbon monoxide, biogenic/ air/ unspecified	8,63E-04	kg
Methane, biogenic/ air/ unspecified	1,54E-04	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	1,67E-05	kg
Nitrogen oxides/ air/ unspecified	4,07E-04	kg
Dinitrogen monoxide/ air/ unspecified	3,07E-06	kg

Sulfur dioxide/ air/ unspecified	7,30E-06	kg
PAH, polycyclic aromatic hydrocarbons/ air/ unspecified	2,05E-09	kg
Particulates, < 2.5 um/ air/ unspecified	1,76E-05	kg
Particulates, > 10 um/ air/ unspecified	2,08E-05	kg
Arsenic/ air/ unspecified	4,46E-10	kg
Cadmium/ air/ unspecified	7,65E-10	kg
Cobalt/ air/ unspecified	8,45E-10	kg
Chromium/ air/ unspecified	1,11E-10	kg
Copper/ air/ unspecified	1,73E-10	kg
Mercury/ air/ unspecified	1,68E-09	kg
Manganese/ air/ unspecified	3,07E-11	kg
Nickel/ air/ unspecified	5,38E-11	kg
Lead/ air/ unspecified	8,45E-11	kg
Antimony/ air/ unspecified	1,73E-10	kg
Selenium/ air/ unspecified	6,91E-10	kg
Thallium/ air/ unspecified	6,91E-10	kg
Vanadium/ air/ unspecified	1,73E-10	kg
Zinc/ air/ unspecified	6,50E-09	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2,96E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air/ unspecified	6,95E-14	kg
Hydrocarbons, aromatic/ air/ unspecified	1,53E-08	kg
Formaldehyde/ air/ unspecified	5,76E-06	kg

Table 50: TOP saw residues inventory

9.5.4 Transport to energy conversion site

Technosphere inputs		
Background Process Name	**Value**	***Unit***
transport, lorry >16t, fleet average/ RER	1,00E+00	tkm

Table 51: inventory for transport to energy conversion site.

9.5.5 Energy conversion

	CHP, electricity		**CHP, heat**	
Technosphere inputs				
Background Process Name	**Value**	***Unit***	**Value**	***Unit***
CHP infrastructure				
	cw	*ww*	*cw*	*ww*
Hard coal power plant, 100MW/GLO/ (p)	3,50E-01	3,50E-01	3,50E-01	3,50E-01
Wood ash to landfilling				
	cw	*ww*	*cw*	*ww*
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH (kg)	1,00E+00	1,00E+00	1,00E+00	1,00E+00

Operation				
	cw	*ww*	*cw*	*ww*
Light fuel oil, at regional storage/RER (kg)	1,70E-05	1,70E-05	1,70E-05	1,70E-05
SOx retained, in hard coal flue gas desulphurisation/RER (kg)	7,04E-06	7,04E-06	7,04E-06	7,04E-06
NOx retained, in SCR/GLO (kg)	1,94E-04	1,94E-04	1,94E-04	1,94E-04
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ (kWh)	9,74E-03	9,74E-03	1,95E-02	1,95E-02
Emissions				
Stressor name	**Value**	***Unit***	**Value**	***Unit***
Combustion emissions				
	cw [kg]	*ww [kg]*	*cw [kg]*	*ww [kg]*
Carbon dioxide, biogenic/ air/ unspecified	9,60E-02	9,60E-02	9,60E-02	9,60E-02
Carbon dioxide, fossil/ air/ unspecified	4,57E-06	4,57E-06	4,57E-06	4,57E-06
Carbon monoxide, biogenic/ air/ unspecified	1,29E-05	1,29E-05	1,29E-05	1,29E-05
Methane, biogenic/ air/ unspecified	3,50E-05	4,00E-05	3,50E-05	4,00E-05
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	5,10E-06	5,10E-06	5,10E-06	5,10E-06
Nitrogen oxides/ air/ unspecified	8,10E-05	7,29E-05	8,10E-05	7,29E-05
Dinitrogen monoxide/ air/ unspecified	1,00E-05	4,00E-06	1,00E-05	4,00E-06
Sulfur dioxide/ air/ unspecified	3,04E-07	3,04E-07	3,04E-07	3,04E-07
Hydrogen chloride/ air/ unspecified	8,37E-06	8,37E-06	8,37E-06	8,37E-06
Hydrogen fluoride/ air/ unspecified	3,80E-09	3,80E-09	3,80E-09	3,80E-09
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air/ unspecified	1,67E-14	1,67E-14	1,67E-14	1,67E-14
PAH, polycyclic aromatic hydrocarbons/ air/ unspecified	6,64E-10	6,64E-10	6,64E-10	6,64E-10
Arsenic/ air/ unspecified	6,09E-10	7,91E-10	6,09E-10	7,91E-10
Cadmium/ air/ unspecified	9,51E-11	9,51E-11	9,51E-11	9,51E-11
Cobalt/ air/ unspecified	2,66E-10	2,66E-10	2,66E-10	2,66E-10
Chromium/ air/ unspecified	2,66E-09	1,05E-08	2,66E-09	1,05E-08
Copper/ air/ unspecified	2,02E-09	7,87E-09	2,02E-09	7,87E-09
Mercury/ air/ unspecified	4,00E-10	4,00E-10	4,00E-10	4,00E-10
Manganese/ air/ unspecified	6,47E-09	4,10E-09	6,47E-09	4,10E-09
Nickel/ air/ unspecified	1,14E-09	2,40E-09	1,14E-09	2,40E-09
Lead/ air/ unspecified	4,19E-09	6,01E-07	4,19E-09	6,01E-07
Antimony/ air/ unspecified	7,61E-11	7,61E-11	7,61E-11	7,61E-11

Thallium/ air/ unspecified	7,61E-12	7,61E-12	7,61E-12	7,61E-12
Vanadium/ air/ unspecified	3,80E-11	9,89E-11	3,80E-11	9,89E-11
Zinc/ air/ unspecified	2,30E-09	7,65E-08	2,30E-09	7,65E-08
Hydrocarbons, aliphatic, alkanes, unspecified	6,10E-06	6,10E-06	6,10E-06	6,10E-06
Hydrocarbons, aromatic/ air/ unspecified	2,31E-09	2,31E-09	2,31E-09	2,31E-09
Particulates, < 2.5 um/ air/ unspecified	4,35E-07	4,35E-07	4,35E-07	4,35E-07
Particulates, > 10 um/ air/ unspecified	5,16E-07	5,16E-07	5,16E-07	5,16E-07
Sulfur/ water/ unspecified	1,14E-05	1,14E-05	1,14E-05	1,14E-05
Chloride/ water/ unspecified	6,56E-06	6,56E-06	6,56E-06	6,56E-06
Calcium, ion/ water/ unspecified	6,64E-06	1,60E-05	6,64E-06	1,60E-05
Magnesium/ water/ unspecified	1,82E-06	2,96E-06	1,82E-06	2,96E-06
Potassium, ion/ water/ ocean	2,46E-05	1,57E-05	2,46E-05	1,57E-05
Sodium, ion/ water/ unspecified	1,42E-06	4,84E-06	1,42E-06	4,84E-06
Zinc, ion/ water/ unspecified	7,08E-08	2,35E-06	7,08E-08	2,35E-06
Wood ash to landfilling				
	cw [kg]	*ww [kg]*	*cw [kg]*	*ww [kg]*
Aluminium/ air/ high population density	1,36E-07	3,82E-07	1,36E-07	3,82E-07
Aluminium/ air/ low population density	2,08E-08	5,84E-08	2,08E-08	5,84E-08
Aluminium/ water/ groundwater	3,32E-02	9,34E-02	3,32E-02	9,34E-02
Aluminium/ water/ river	4,98E-06	1,40E-05	4,98E-06	1,40E-05
Arsenic, ion/ water/ groundwater	-1,86E-06	-1,86E-06	-1,86E-06	-1,86E-06
Arsenic, ion/ water/ river	-1,48E-08	-1,48E-08	-1,48E-08	-1,48E-08
Arsenic/ air/ high population density	-4,72E-12	-4,72E-12	-4,72E-12	-4,72E-12
Arsenic/ air/ low population density	-2,35E-10	-2,35E-10	-2,35E-10	-2,35E-10
BOD5, Biological Oxygen Demand/ water/ groundwater	1,01E-01	1,01E-01	1,01E-01	1,01E-01
BOD5, Biological Oxygen Demand/ water/ river	4,65E-04	4,65E-04	4,65E-04	4,65E-04
Cadmium, ion/ water/ groundwater	-1,21E-05	-1,21E-05	-1,21E-05	-1,21E-05
Cadmium, ion/ water/ river	-5,43E-08	-5,43E-08	-5,43E-08	-5,43E-08
Cadmium/ air/ high population density	-2,93E-12	-2,93E-12	-2,93E-12	-2,93E-12
Cadmium/ air/ low population density	-7,13E-10	-7,13E-10	-7,13E-10	-7,13E-10
Calcium, ion/ water/ groundwater	-2,56E-03	-3,79E-02	-2,56E-03	-3,79E-02

Calcium, ion/ water/ river	-1,51E-05	-2,24E-04	-1,51E-05	-2,24E-04
Calcium/ air/ high population density	-2,74E-09	-4,06E-08	-2,74E-09	-4,06E-08
Calcium/ air/ low population density	-4,19E-09	-6,21E-08	-4,19E-09	-6,21E-08
Carbon dioxide, biogenic/ air/ high population density	1,45E-03	1,45E-03	1,45E-03	1,45E-03
Carbon dioxide, biogenic/ air/ low population density	4,33E-02	4,33E-02	4,33E-02	4,33E-02
Chloride/ water/ groundwater	-2,69E-03	-2,69E-03	-2,69E-03	-2,69E-03
Chloride/ water/ river	-5,01E-04	-5,01E-04	-5,01E-04	-5,01E-04
Chromium VI/ water/ groundwater	7,50E-04	5,14E-04	7,50E-04	5,14E-04
Chromium VI/ water/ river	4,92E-05	3,37E-05	4,92E-05	3,37E-05
Chromium, ion/ water/ river	1,47E-07	1,01E-07	1,47E-07	1,01E-07
Chromium/ air/ high population density	3,42E-12	2,35E-12	3,42E-12	2,35E-12
Chromium/ air/ low population density	2,35E-08	1,61E-08	2,35E-08	1,61E-08
Cobalt/ air/ high population density	-4,06E-16	-4,06E-16	-4,06E-16	-4,06E-16
Cobalt/ air/ low population density	-6,50E-12	-6,50E-12	-6,50E-12	-6,50E-12
Cobalt/ water/ groundwater	-1,60E-06	-1,60E-06	-1,60E-06	-1,60E-06
Cobalt/ water/ river	-1,32E-08	-1,32E-08	-1,32E-08	-1,32E-08
Copper, ion/ water/ groundwater	9,01E-04	4,39E-03	9,01E-04	4,39E-03
Copper, ion/ water/ river	5,75E-08	2,80E-07	5,75E-08	2,80E-07
Copper/ air/ high population density	1,20E-12	5,88E-12	1,20E-12	5,88E-12
Copper/ air/ low population density	6,30E-11	3,07E-10	6,30E-11	3,07E-10
Iron, ion/ water/ groundwater	3,36E-02	5,12E-02	3,36E-02	5,12E-02
Iron, ion/ water/ river	1,63E-04	2,48E-04	1,63E-04	2,48E-04
Iron/ air/ high population density	7,92E-08	1,21E-07	7,92E-08	1,21E-07
Iron/ air/ low population density	7,98E-08	1,22E-07	7,98E-08	1,22E-07
Lead/ air/ high population density	1,66E-13	4,30E-12	1,66E-13	4,30E-12
Lead/ air/ low population density	1,67E-12	4,33E-11	1,67E-12	4,33E-11
Lead/ water/ groundwater	1,71E-05	4,41E-04	1,71E-05	4,41E-04
Lead/ water/ river	5,51E-10	1,43E-08	5,51E-10	1,43E-08
Magnesium/ air/ high population density	3,61E-08	8,27E-09	3,61E-08	8,27E-09
Magnesium/ air/ low population density	6,69E-08	1,53E-08	6,69E-08	1,53E-08

Magnesium/ water/ groundwater	8,41E-03	1,93E-03	8,41E-03	1,93E-03
Magnesium/ water/ river	2,41E-04	5,52E-05	2,41E-04	5,52E-05
Manganese/ air/ high population density	-6,11E-13	-6,11E-13	-6,11E-13	-6,11E-13
Manganese/ air/ low population density	-5,71E-08	-5,71E-08	-5,71E-08	-5,71E-08
Manganese/ water/ groundwater	-3,77E-03	-3,77E-03	-3,77E-03	-3,77E-03
Manganese/ water/ river	-1,16E-04	-1,16E-04	-1,16E-04	-1,16E-04
Molybdenum/ air/ high population density	2,43E-11	2,43E-11	2,43E-11	2,43E-11
Molybdenum/ air/ low population density	6,17E-12	6,17E-12	6,17E-12	6,17E-12
Molybdenum/ water/ groundwater	1,85E-06	1,85E-06	1,85E-06	1,85E-06
Molybdenum/ water/ river	1,46E-08	1,46E-08	1,46E-08	1,46E-08
Nickel, ion/ water/ groundwater	3,51E-05	7,47E-05	3,51E-05	7,47E-05
Nickel, ion/ water/ river	6,20E-08	1,32E-07	6,20E-08	1,32E-07
Nickel/ air/ high population density	1,74E-15	3,70E-15	1,74E-15	3,70E-15
Nickel/ air/ low population density	2,55E-11	5,43E-11	2,55E-11	5,43E-11
Phosphate/ water/ groundwater	1,28E-02	1,08E-02	1,28E-02	1,08E-02
Phosphate/ water/ river	1,85E-03	1,56E-03	1,85E-03	1,56E-03
Phosphorus/ air/ high population density	-2,62E-05	2,81E-06	-2,62E-05	2,81E-06
Potassium, ion/ water/ groundwater	-1,79E-04	-3,14E-02	-1,79E-04	-3,14E-02
Potassium, ion/ water/ river	-6,79E-06	-1,19E-03	-6,79E-06	-1,19E-03
Potassium/ air/ low population density	-1,70E-09	-2,98E-07	-1,70E-09	-2,98E-07
Silicon/ air/ high population density	6,53E-05	6,13E-05	6,53E-05	6,13E-05
Silicon/ air/ low population density	7,45E-06	7,00E-06	7,45E-06	7,00E-06
Silicon/ water/ groundwater	2,30E-01	2,16E-01	2,30E-01	2,16E-01
Silicon/ water/ river	1,79E-03	1,68E-03	1,79E-03	1,68E-03
Sulfate/ water/ groundwater	-4,14E-03	3,64E-03	-4,14E-03	3,64E-03
Sulfate/ water/ river	-1,05E-04	9,21E-05	-1,05E-04	9,21E-05
Titanium, ion/ water/ groundwater	-1,08E-03	-1,08E-03	-1,08E-03	-1,08E-03
Titanium, ion/ water/ river	-1,75E-06	-1,75E-06	-1,75E-06	-1,75E-06
Titanium/ air/ high population density	-1,70E-09	-1,70E-09	-1,70E-09	-1,70E-09
Titanium/ air/ low population density	-8,64E-10	-8,64E-10	-8,64E-10	-8,64E-10

TOC, Total Organic Carbon/ water/ groundwater	4,26E-03	-2,42E-03	4,26E-03	-2,42E-03
TOC, Total Organic Carbon/ water/ river	4,07E-06	-2,31E-06	4,07E-06	-2,31E-06
Vanadium, ion/ water/ groundwater	2,13E-05	2,13E-05	2,13E-05	2,13E-05
Vanadium, ion/ water/ river	1,96E-07	1,96E-07	1,96E-07	1,96E-07
Vanadium/ air/ high population density	1,90E-11	1,90E-11	1,90E-11	1,90E-11
Vanadium/ air/ low population density	9,63E-11	9,63E-11	9,63E-11	9,63E-11
Zinc, ion/ water/ groundwater	-9,31E-04	3,48E-04	-9,31E-04	3,48E-04
Zinc, ion/ water/ river	-8,29E-07	3,10E-07	-8,29E-07	3,10E-07
Zinc/ air/ high population density/ air/ high population density	-3,02E-11	1,13E-11	-3,02E-11	1,13E-11
Zinc/ air/ low population density	-5,94E-10	2,22E-10	-5,94E-10	2,22E-10
Sodium, ion/ water/ unspecified	9,43E-03	1,02E-02	9,43E-03	1,02E-02
Barium/ water/ unspecified	7,97E-04	7,97E-04	7,97E-04	7,97E-04

Table 52: CHP, electricity and CHP, heat inventories.

	Thermal, electricity		**DH, heat**		**Boiler, steam**	
Technosphere inputs						
Background Process Name	**Value**	***Unit***	**Value**	***Unit***	**Value**	***Unit***
Infrastructure	*cw*	*ww*	*cw*	*ww*	*cw*	*ww*
Hard coal power plant, 100MW/GLO/ (p)	3,50E-01	3,50E-01	3,50E+00	3,50E+00	3,50E+00	3,50E+00
Wood ash to landfilling	*cw*	*ww*	*cw*	*ww*	*cw*	*ww*
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH (kg)	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
Operation	*cw*	*ww*	*cw*	*ww*	*cw*	*ww*
Light fuel oil, at regional storage/RER (kg)	1,70E-05	1,70E-05	1,70E-05	1,70E-05	1,70E-05	1,70E-05
SOx retained, in hard coal flue gas desulphurisation/RER (kg)	7,04E-06	7,04E-06	7,04E-06	7,04E-06	7,04E-06	7,04E-06
NOx retained, in SCR/GLO (kg)	1,94E-04	1,94E-04	1,94E-04	1,94E-04	1,94E-04	1,94E-04
electricity, medium voltage, production NORDEL, at grid/ NORDEL/ (kWh)	1,17E-02	1,17E-02	1,31E-02	1,31E-02	1,35E-02	1,35E-02
Emissions						
Stressor name	**Value**	***Unit***	**Value**	***Unit***	**Value**	***Unit***
Combustion emissions	*cw [kg]*	*ww [kg]*	*cw [kg]*	*ww [kg]*	*cw [kg]*	*ww [kg]*
Carbon dioxide, biogenic/ air/ unspecified	9,60E-02	9,60E-02	9,60E-02	9,60E-02	9,60E-02	9,60E-02

Carbon dioxide, fossil/ air/ unspecified	4,57E-06	4,57E-06	4,57E-06	4,57E-06	4,57E-06	4,57E-06
Carbon monoxide, biogenic/ air/ unspecified	1,29E-05	1,29E-05	1,29E-05	1,29E-05	1,29E-05	1,29E-05
Methane, biogenic/ air/ unspecified	3,50E-05	4,00E-05	3,50E-05	4,00E-05	3,50E-05	4,00E-05
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	5,10E-06	5,10E-06	5,10E-06	5,10E-06	5,10E-06	5,10E-06
Nitrogen oxides/ air/ unspecified	8,10E-05	7,29E-05	8,10E-05	7,29E-05	8,10E-05	7,29E-05
Dinitrogen monoxide/ air/ unspecified	1,00E-05	4,00E-06	1,00E-05	4,00E-06	1,00E-05	4,00E-06
Sulfur dioxide/ air/ unspecified	3,04E-07	3,04E-07	3,04E-07	3,04E-07	3,04E-07	3,04E-07
Hydrogen chloride/ air/ unspecified	8,37E-06	8,37E-06	8,37E-06	8,37E-06	8,37E-06	8,37E-06
Hydrogen fluoride/ air/ unspecified	3,80E-09	3,80E-09	3,80E-09	3,80E-09	3,80E-09	3,80E-09
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air/ unspecified	1,67E-14	1,67E-14	1,67E-14	1,67E-14	1,67E-14	1,67E-14
PAH, polycyclic aromatic hydrocarbons/ air/ unspecified	6,64E-10	6,64E-10	6,64E-10	6,64E-10	6,64E-10	6,64E-10
Arsenic/ air/ unspecified	6,09E-10	7,91E-10	6,09E-10	7,91E-10	6,09E-10	7,91E-10
Cadmium/ air/ unspecified	9,51E-11	9,51E-11	9,51E-11	9,51E-11	9,51E-11	9,51E-11
Cobalt/ air/ unspecified	2,66E-10	2,66E-10	2,66E-10	2,66E-10	2,66E-10	2,66E-10
Chromium/ air/ unspecified	2,66E-09	1,05E-08	2,66E-09	1,05E-08	2,66E-09	1,05E-08
Copper/ air/ unspecified	2,02E-09	7,87E-09	2,02E-09	7,87E-09	2,02E-09	7,87E-09
Mercury/ air/ unspecified	4,00E-10	4,00E-10	4,00E-10	4,00E-10	4,00E-10	4,00E-10
Manganese/ air/ unspecified	6,47E-09	4,10E-09	6,47E-09	4,10E-09	6,47E-09	4,10E-09
Nickel/ air/ unspecified	1,14E-09	2,40E-09	1,14E-09	2,40E-09	1,14E-09	2,40E-09
Lead/ air/ unspecified	4,19E-09	6,01E-07	4,19E-09	6,01E-07	4,19E-09	6,01E-07
Antimony/ air/ unspecified	7,61E-11	7,61E-11	7,61E-11	7,61E-11	7,61E-11	7,61E-11
Thallium/ air/ unspecified	7,61E-12	7,61E-12	7,61E-12	7,61E-12	7,61E-12	7,61E-12
Vanadium/ air/ unspecified	3,80E-11	9,89E-11	3,80E-11	9,89E-11	3,80E-11	9,89E-11
Zinc/ air/ unspecified	2,30E-09	7,65E-08	2,30E-09	7,65E-08	2,30E-09	7,65E-08
Hydrocarbons, aliphatic, alkanes, unspecified	6,10E-06	6,10E-06	6,10E-06	6,10E-06	6,10E-06	6,10E-06
Hydrocarbons, aromatic/ air/ unspecified	2,31E-09	2,31E-09	2,31E-09	2,31E-09	2,31E-09	2,31E-09
Particulates, < 2.5 um/ air/ unspecified	4,35E-07	4,35E-07	4,35E-07	4,35E-07	4,35E-07	4,35E-07
Particulates, > 10 um/ air/ unspecified	5,16E-07	5,16E-07	5,16E-07	5,16E-07	5,16E-07	5,16E-07
Sulfur/ water/ unspecified	1,14E-05	1,14E-05	1,14E-05	1,14E-05	1,14E-05	1,14E-05
Chloride/ water/ unspecified	6,56E-06	6,56E-06	6,56E-06	6,56E-06	6,56E-06	6,56E-06

Calcium, ion/ water/ unspecified	6,64E-06	1,60E-05	6,64E-06	1,60E-05	6,64E-06	1,60E-05
Magnesium/ water/ unspecified	1,82E-06	2,96E-06	1,82E-06	2,96E-06	1,82E-06	2,96E-06
Potassium, ion/ water/ ocean	2,46E-05	1,57E-05	2,46E-05	1,57E-05	2,46E-05	1,57E-05
Sodium, ion/ water/ unspecified	1,42E-06	4,84E-06	1,42E-06	4,84E-06	1,42E-06	4,84E-06
Zinc, ion/ water/ unspecified	7,08E-08	2,35E-06	7,08E-08	2,35E-06	7,08E-08	2,35E-06
Wood ash to landfilling	*cw [kg]*	*ww [kg]*	*cw [kg]*	*ww [kg]*	*cw [kg]*	*ww [kg]*
Aluminium/ air/ high population density	1,36E-07	3,82E-07	1,36E-07	3,82E-07	1,36E-07	3,82E-07
Aluminium/ air/ low population density	2,08E-08	5,84E-08	2,08E-08	5,84E-08	2,08E-08	5,84E-08
Aluminium/ water/ groundwater	3,32E-02	9,34E-02	3,32E-02	9,34E-02	3,32E-02	9,34E-02
Aluminium/ water/ river	4,98E-06	1,40E-05	4,98E-06	1,40E-05	4,98E-06	1,40E-05
Arsenic, ion/ water/ groundwater	-1,86E-06	-1,86E-06	-1,86E-06	-1,86E-06	-1,86E-06	-1,86E-06
Arsenic, ion/ water/ river	-1,48E-08	-1,48E-08	-1,48E-08	-1,48E-08	-1,48E-08	-1,48E-08
Arsenic/ air/ high population density	-4,72E-12	-4,72E-12	-4,72E-12	-4,72E-12	-4,72E-12	-4,72E-12
Arsenic/ air/ low population density	-2,35E-10	-2,35E-10	-2,35E-10	-2,35E-10	-2,35E-10	-2,35E-10
BOD5, Biological Oxygen Demand/ water/ groundwater	1,01E-01	1,01E-01	1,01E-01	1,01E-01	1,01E-01	1,01E-01
BOD5, Biological Oxygen Demand/ water/ river	4,65E-04	4,65E-04	4,65E-04	4,65E-04	4,65E-04	4,65E-04
Cadmium, ion/ water/ groundwater	-1,21E-05	-1,21E-05	-1,21E-05	-1,21E-05	-1,21E-05	-1,21E-05
Cadmium, ion/ water/ river	-5,43E-08	-5,43E-08	-5,43E-08	-5,43E-08	-5,43E-08	-5,43E-08
Cadmium/ air/ high population density	-2,93E-12	-2,93E-12	-2,93E-12	-2,93E-12	-2,93E-12	-2,93E-12
Cadmium/ air/ low population density	-7,13E-10	-7,13E-10	-7,13E-10	-7,13E-10	-7,13E-10	-7,13E-10
Calcium, ion/ water/ groundwater	-2,56E-03	-3,79E-02	-2,56E-03	-3,79E-02	-2,56E-03	-3,79E-02
Calcium, ion/ water/ river	-1,51E-05	-2,24E-04	-1,51E-05	-2,24E-04	-1,51E-05	-2,24E-04
Calcium/ air/ high population density	-2,74E-09	-4,06E-08	-2,74E-09	-4,06E-08	-2,74E-09	-4,06E-08
Calcium/ air/ low population density	-4,19E-09	-6,21E-08	-4,19E-09	-6,21E-08	-4,19E-09	-6,21E-08

Carbon dioxide, biogenic/ air/ high population density	1,45E-03	1,45E-03	1,45E-03	1,45E-03	1,45E-03	1,45E-03
Carbon dioxide, biogenic/ air/ low population density	4,33E-02	4,33E-02	4,33E-02	4,33E-02	4,33E-02	4,33E-02
Chloride/ water/ groundwater	-2,69E-03	-2,69E-03	-2,69E-03	-2,69E-03	-2,69E-03	-2,69E-03
Chloride/ water/ river	-5,01E-04	-5,01E-04	-5,01E-04	-5,01E-04	-5,01E-04	-5,01E-04
Chromium VI/ water/ groundwater	7,50E-04	5,14E-04	7,50E-04	5,14E-04	7,50E-04	5,14E-04
Chromium VI/ water/ river	4,92E-05	3,37E-05	4,92E-05	3,37E-05	4,92E-05	3,37E-05
Chromium, ion/ water/ river	1,47E-07	1,01E-07	1,47E-07	1,01E-07	1,47E-07	1,01E-07
Chromium/ air/ high population density	3,42E-12	2,35E-12	3,42E-12	2,35E-12	3,42E-12	2,35E-12
Chromium/ air/ low population density	2,35E-08	1,61E-08	2,35E-08	1,61E-08	2,35E-08	1,61E-08
Cobalt/ air/ high population density	-4,06E-16	-4,06E-16	-4,06E-16	-4,06E-16	-4,06E-16	-4,06E-16
Cobalt/ air/ low population density	-6,50E-12	-6,50E-12	-6,50E-12	-6,50E-12	-6,50E-12	-6,50E-12
Cobalt/ water/ groundwater	-1,60E-06	-1,60E-06	-1,60E-06	-1,60E-06	-1,60E-06	-1,60E-06
Cobalt/ water/ river	-1,32E-08	-1,32E-08	-1,32E-08	-1,32E-08	-1,32E-08	-1,32E-08
Copper, ion/ water/ groundwater	9,01E-04	4,39E-03	9,01E-04	4,39E-03	9,01E-04	4,39E-03
Copper, ion/ water/ river	5,75E-08	2,80E-07	5,75E-08	2,80E-07	5,75E-08	2,80E-07
Copper/ air/ high population density	1,20E-12	5,88E-12	1,20E-12	5,88E-12	1,20E-12	5,88E-12
Copper/ air/ low population density	6,30E-11	3,07E-10	6,30E-11	3,07E-10	6,30E-11	3,07E-10
Iron, ion/ water/ groundwater	3,36E-02	5,12E-02	3,36E-02	5,12E-02	3,36E-02	5,12E-02
Iron, ion/ water/ river	1,63E-04	2,48E-04	1,63E-04	2,48E-04	1,63E-04	2,48E-04
Iron/ air/ high population density	7,92E-08	1,21E-07	7,92E-08	1,21E-07	7,92E-08	1,21E-07
Iron/ air/ low population density	7,98E-08	1,22E-07	7,98E-08	1,22E-07	7,98E-08	1,22E-07
Lead/ air/ high population density	1,66E-13	4,30E-12	1,66E-13	4,30E-12	1,66E-13	4,30E-12
Lead/ air/ low population density	1,67E-12	4,33E-11	1,67E-12	4,33E-11	1,67E-12	4,33E-11
Lead/ water/ groundwater	1,71E-05	4,41E-04	1,71E-05	4,41E-04	1,71E-05	4,41E-04
Lead/ water/ river	5,51E-10	1,43E-08	5,51E-10	1,43E-08	5,51E-10	1,43E-08
Magnesium/ air/ high population density	3,61E-08	8,27E-09	3,61E-08	8,27E-09	3,61E-08	8,27E-09
Magnesium/ air/ low population density	6,69E-08	1,53E-08	6,69E-08	1,53E-08	6,69E-08	1,53E-08
Magnesium/ water/ groundwater	8,41E-	1,93E-	8,41E-	1,93E-	8,41E-	1,93E-

	03	03	03	03	03	03
Magnesium/ water/ river	2,41E-04	5,52E-05	2,41E-04	5,52E-05	2,41E-04	5,52E-05
Manganese/ air/ high population density	-6,11E-13	-6,11E-13	-6,11E-13	-6,11E-13	-6,11E-13	-6,11E-13
Manganese/ air/ low population density	-5,71E-08	-5,71E-08	-5,71E-08	-5,71E-08	-5,71E-08	-5,71E-08
Manganese/ water/ groundwater	-3,77E-03	-3,77E-03	-3,77E-03	-3,77E-03	-3,77E-03	-3,77E-03
Manganese/ water/ river	-1,16E-04	-1,16E-04	-1,16E-04	-1,16E-04	-1,16E-04	-1,16E-04
Molybdenum/ air/ high population density	2,43E-11	2,43E-11	2,43E-11	2,43E-11	2,43E-11	2,43E-11
Molybdenum/ air/ low population density	6,17E-12	6,17E-12	6,17E-12	6,17E-12	6,17E-12	6,17E-12
Molybdenum/ water/ groundwater	1,85E-06	1,85E-06	1,85E-06	1,85E-06	1,85E-06	1,85E-06
Molybdenum/ water/ river	1,46E-08	1,46E-08	1,46E-08	1,46E-08	1,46E-08	1,46E-08
Nickel, ion/ water/ groundwater	3,51E-05	7,47E-05	3,51E-05	7,47E-05	3,51E-05	7,47E-05
Nickel, ion/ water/ river	6,20E-08	1,32E-07	6,20E-08	1,32E-07	6,20E-08	1,32E-07
Nickel/ air/ high population density	1,74E-15	3,70E-15	1,74E-15	3,70E-15	1,74E-15	3,70E-15
Nickel/ air/ low population density	2,55E-11	5,43E-11	2,55E-11	5,43E-11	2,55E-11	5,43E-11
Phosphate/ water/ groundwater	1,28E-02	1,08E-02	1,28E-02	1,08E-02	1,28E-02	1,08E-02
Phosphate/ water/ river	1,85E-03	1,56E-03	1,85E-03	1,56E-03	1,85E-03	1,56E-03
Phosphorus/ air/ high population density	-2,62E-05	2,81E-06	-2,62E-05	2,81E-06	-2,62E-05	2,81E-06
Potassium, ion/ water/ groundwater	-1,79E-04	-3,14E-02	-1,79E-04	-3,14E-02	-1,79E-04	-3,14E-02
Potassium, ion/ water/ river	-6,79E-06	-1,19E-03	-6,79E-06	-1,19E-03	-6,79E-06	-1,19E-03
Potassium/ air/ low population density	-1,70E-09	-2,98E-07	-1,70E-09	-2,98E-07	-1,70E-09	-2,98E-07
Silicon/ air/ high population density	6,53E-05	6,13E-05	6,53E-05	6,13E-05	6,53E-05	6,13E-05
Silicon/ air/ low population density	7,45E-06	7,00E-06	7,45E-06	7,00E-06	7,45E-06	7,00E-06
Silicon/ water/ groundwater	2,30E-01	2,16E-01	2,30E-01	2,16E-01	2,30E-01	2,16E-01
Silicon/ water/ river	1,79E-03	1,68E-03	1,79E-03	1,68E-03	1,79E-03	1,68E-03
Sulfate/ water/ groundwater	-4,14E-03	3,64E-03	-4,14E-03	3,64E-03	-4,14E-03	3,64E-03
Sulfate/ water/ river	-1,05E-04	9,21E-05	-1,05E-04	9,21E-05	-1,05E-04	9,21E-05

Titanium, ion/ water/ groundwater	-1,08E-03	-1,08E-03	-1,08E-03	-1,08E-03	-1,08E-03	-1,08E-03
Titanium, ion/ water/ river	-1,75E-06	-1,75E-06	-1,75E-06	-1,75E-06	-1,75E-06	-1,75E-06
Titanium/ air/ high population density	-1,70E-09	-1,70E-09	-1,70E-09	-1,70E-09	-1,70E-09	-1,70E-09
Titanium/ air/ low population density	-8,64E-10	-8,64E-10	-8,64E-10	-8,64E-10	-8,64E-10	-8,64E-10
TOC, Total Organic Carbon/ water/ groundwater	4,26E-03	-2,42E-03	4,26E-03	-2,42E-03	4,26E-03	-2,42E-03
TOC, Total Organic Carbon/ water/ river	4,07E-06	-2,31E-06	4,07E-06	-2,31E-06	4,07E-06	-2,31E-06
Vanadium, ion/ water/ groundwater	2,13E-05	2,13E-05	2,13E-05	2,13E-05	2,13E-05	2,13E-05
Vanadium, ion/ water/ river	1,96E-07	1,96E-07	1,96E-07	1,96E-07	1,96E-07	1,96E-07
Vanadium/ air/ high population density	1,90E-11	1,90E-11	1,90E-11	1,90E-11	1,90E-11	1,90E-11
Vanadium/ air/ low population density	9,63E-11	9,63E-11	9,63E-11	9,63E-11	9,63E-11	9,63E-11
Zinc, ion/ water/ groundwater	-9,31E-04	3,48E-04	-9,31E-04	3,48E-04	-9,31E-04	3,48E-04
Zinc, ion/ water/ river	-8,29E-07	3,10E-07	-8,29E-07	3,10E-07	-8,29E-07	3,10E-07
Zinc/ air/ high population density/ air/ high population density	-3,02E-11	1,13E-11	-3,02E-11	1,13E-11	-3,02E-11	1,13E-11
Zinc/ air/ low population density	-5,94E-10	2,22E-10	-5,94E-10	2,22E-10	-5,94E-10	2,22E-10
Sodium, ion/ water/ unspecified	9,43E-03	1,02E-02	9,43E-03	1,02E-02	9,43E-03	1,02E-02
Barium/ water/ unspecified	7,97E-04	7,97E-04	7,97E-04	7,97E-04	7,97E-04	7,97E-04

Table 53: Thermal, electricity, DH, heat and boiler, steam inventories.

9.5.6 Distribution

Electricity distribution		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Electricity to end user		
Electricity, high voltage, production NORDEL, at grid	1	kWh
Electricity, production mix NORDEL	-1,0095	kWh

Table 54: electricity distribution inventory.

Heat distribution		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Heat to end user		
steel, low-alloyed, at plant/ RER/ kg	2,77E-03	kg
polyethylene, HDPE, granulate, at plant/ RER/ kg	1,49E-03	kg
copper, at regional storage/ RER/ kg	8,13E-06	kg
pentane, at plant/ RER/ kg	3,35E-05	kg
synthetic rubber, at plant/ RER/ kg	2,66E-04	kg
polyvinylchloride, at regional storage/ RER/ kg	5,83E-06	kg
toluene diisocyanate, at plant/ RER/ kg	6,16E-04	kg
polyurethane, flexible foam, at plant/ RER/ kg	1,06E-03	kg
gravel, unspecified, at mine/ CH/ kg	1,13E-01	kg
sand, at mine/ CH/ kg	3,46E-01	kg
mastic asphalt, at plant/ CH/ kg	1,25E-01	kg
excavation, hydraulic digger/ RER/ m3	2,36E-04	m3
transport, lorry >16t, fleet average/ RER/ tkm	1,37E-02	tkm

Table 55: heat distribution inventory.

Steam distribution		
Technosphere inputs		
Background Process Name	**Value**	***Unit***
Steam to end user		
steel, low-alloyed, at plant/ RER/ kg	4,05E-04	kg
polyethylene, HDPE, granulate, at plant/ RER/ kg	1,31E-04	kg
copper, at regional storage/ RER/ kg	2,71E-06	kg
pentane, at plant/ RER/ kg	3,38E-06	kg
synthetic rubber, at plant/ RER/ kg	1,02E-04	kg
polyvinylchloride, at regional storage/ RER/ kg	5,51E-07	kg
toluene diisocyanate, at plant/ RER/ kg	6,16E-05	kg
polyurethane, flexible foam, at plant/ RER/ kg	1,06E-04	kg

Table 56: steam distribution inventory.

9.6 Appendix 6: foreground matrices

The foreground matrices for the different process steps and alternatives are presented here.

9.6.1 Feedstock

The feedstock foreground system is put together from the tables shown below.

		1	2	3	4	5	6	7	8	9	10	11	12	13
1: Harvesting softwood	m3			0,87										
2: Harvesting hardwood	m3			0,13										
3: Harvesting total	m3				0,82									
4: Storage in forest	m3					1,40E-03								
5: Storage in forest: m3->kg	kg						1,02							
6: Storage in forest: mass losses	kg							714,8						
7: Storage in forest: kg->m3	m3									1				
8: Forwarding	tkm									0,36				
9: Storage at forest road	m3										1,63E-03			
10: Storage at forest road: m3->kg	kg											1		
11: Storage at forest road: mass losses	kg												1	
12: Storage at forest road: kg->kg	kg													1
13: Dummy stemwood	kg													

Table 57: stemwood part of the feedstock foreground matrix.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1: Harvesting softwood residues	m3			0,87											
2: Harvesting hardwood residues	m3			0,13											
3: Harvesting total forest residues	m3				0,16										
4: Storage in forest	m3					8,75E-03									
5: Storage in forest: m3->kg	kg						1,18								
6: Storage in forest: mass	kg							114,2							

losses								9							
7: Storage in forest: kg->m3	m3								1,40						
8: Baling	m3										1				
9: Forwarding	tkm										0,079				
10: Storage at forest road	m3											6,36E-03			
11: Storage at forest road: m3->kg	kg												1,02		
12: Storage at forest road: mass losses	kg													1	
13: Storage at forest road: kg->kg	kg														1
14: Dummy FR	kg														

Table 58: forest residues part of the feedstock foreground matrix.

		1	2	3	4	5	6	7	8	9	10	11	12	13
1: Harvesting softwood	m3			0,87										
2: Harvesting hardwood	m3			0,13										
3: Harvesting total	m3				1,02									
4: Storage in forest	m3					1,48E-03								
5: Storage in forest: m3->kg	kg						1,02							
6: Storage in forest: mass losses	kg							673,8						
7: Storage in forest: kg->m3	m3									1				
8: Forwarding	tkm									0,337				
9: Storage at forest road	m3										1,48E-03			
10: Storage at forest road: m3->kg	kg											1		
11: Storage at forest road: mass losses	kg												1	
12: Storage at forest road: kg->kg	kg													1
13: Dummy energy wood	kg													

Table 59: energy wood part of the feedstock foreground matrix.

		1	2	3	4	5	6	7	8	9	10	11
1: Collection SR softwood	m3			0,99								
2: Collection SR hardwood	m3			0,01								
3: Collection SR total	m3				5,67E-03							
4: Collection SR total: m3->kg	kg									1		
5: Collection P&C	m3						6,38E-03					
6: Collection P&C: m3->kg	kg										1	

7: Collection WW	m3								0,050			
8: Collection WW: m3->kg	kg											1
9: Dummy SR	kg											
10: Dummy P&C waste	kg											
11: Dummy wood waste	kg											

Table 60: saw residues, P&C waste and wood waste parts of the feedstock foreground matrix.

Dummys		**y_f:**	1	2	3	4	5	6	7
1: Stemwood	kg								0
2: Forest residues	kg								0
3: Energy wood	kg								0
4: Saw residues	kg								0
5: P&C waste	kg								0
6: wood waste	kg								0
7: Feedstock choice	kg	1							

Table 61: final part of the feedstock foreground matrix, including final demand.

9.6.2 Transport to treatment site

		1	2
1: Transport to pre-treatment site	tkm		0,001
2: Dummy	kg		

Table 62: foreground system for the transport to energy conversion site step.

9.6.3 Treatment

		1	2	3	4	5	6
1: Chipping	m3		0,004				
2: Chips storage at site	kg			1,0			
3: Chips storage at site: m3->kg	kg				1,02		
4: Chips storage at site: mass losses	kg					0,1	
5: Chips storage at site: kg->m3	MJ(db)						1,00
6: Chipping dummy	MJ(db)						

Table 63: chipping part of the treatment foreground matrix.

		1	2	3	4	5	6	7	8	9	10	11	12
1: Chipping	m3		0,004										
2: Chips storage	kg			1,0									
3: Chips storage: m3->kg	kg				1,02								

4: Chips storage: mass losses	kg					259,1							
5: Chips storage: kg->m3	m3						1,0						
6: Pre-treatment and drying	m3							1					
7: Pelletising	m3								1				
8: Pellet storage at site	m3									0,0015			
9: Pellet storage at site: m3->kg	kg										1		
10: Pellet storage at site: mass losses	kg											5,32E-02	
11: Pellet storage at site: kg->m3	MJ(db)												1,00
12: Pelletising dummy	MJ(db)												

Table 64: pelletising part of the treatment foreground matrix.

		1	2	3	4	5	6	7	8	9	10
1: Chipping	m3		0,004								
2: Chips storage at site	kg			1,0							
3: Chips storage at site: m3->kg	kg				1,02						
4: Chips storage at site: mass losses	kg							1			
5: TOP infrastructure	p							3,66E-09			
6: TOP ash to landfilling	kg							3,41E-04			
7: TOP (kg)	kg								1		
8: TOP storage: mass losses	kg									0,047	
9: TOP storage: kg->m3	MJ(db)										1,00
10: Torrefaction cw dummy	MJ(db)										

Table 65: clean wood torrefaction part of the treatment foreground matrix.

		1	2	3	4	5	6	7	8	9	10
1: Chipping	m3		0,004								
2: Chips storage at site	m3			1,0							
3: Chips storage at site: m3->kg	kg				1,02						
4: Chips storage at site: mass losses	kg							1,00			
5: TOP infrastructure	p							3,66E-09			
6: TOP ash to landfilling	kg							3,41E-04			
7: TOP (kg)	kg								1		
8: TOP storage: mass losses	kg									4,68E-02	
9: TOP storage: kg->m3	MJ(db)										1,00
10: Torrefaction ww dummy	MJ(db)										

Table 66: waste wood torrefaction part of the treatment foreground matrix.

		1	2	3	4	5
1: SR storage	m3		0,007			

2: SR storage: kg->kg	kg			1,05		
3: SR storage: mass losses	kg				0,05	
4: SR storage: kg->m3	MJ(db)					1,00
5: SR direct dummy	MJ(db)					

Table 67: saw residues direct part of the treatment foreground matrix.

		1	2	3	4	5	6	7	8	9	10	11
1: SR storage	m3		0,007									
2: SR storage: kg->kg	kg			1,05								
3: SR storage: mass losses	kg				141,2							
4: SR storage: kg->m3	m3					1						
5: Pre-treatment and drying	m3						1					
6: Pelletising	m3							1				
7: Pellet storage	m3								0,0015			
8: Pellet storage: m3->kg	kg									1		
9: Pellet storage: mass losses	kg										5,32E-02	
10: Pellet storage: kg->m3	MJ(db)											1,00
11: SR pellet dummy	MJ(db)											

Table 68: saw residues pelletising part of the treatment foreground matrix.

		1	2	3	4	5	6	7	8	9	10
1: SR storage	m3		0,007								
2: SR storage: kg->kg	kg			1,05							
3: SR storage: mass losses	kg				141,2						
4: SR storage: kg->m3	m3							0,007			
5: TOP infrastructure	p							3,66E-09			
6: TOP ash to landfarming	m3							3,41E-04			
7: TOP (kg)	kg								1		
8: TOP storage: mass losses	kg									4,68E-02	
9: TOP storage: kg->m3	MJ(db)										1,00
10: SR TOP dummy	MJ(db)										

Table 69: saw residues TOP part of the treatment foreground matrix.

Dummys		**y_f:**	1	2	3	4	5	6	7	8
1: Chipping	MJ(db)									0
2: Pelletising	MJ(db)									0
3: Torrefaction cw	MJ(db)									0
4: Torrefaction ww	MJ(db)									0
5: SR direct	MJ(db)									0
6: SR pellet	MJ(db)									0
7: SR TOP	MJ(db)									0

Pre-treatment choice	MJ(db)	1								

Table 70: final part of treatment foreground matrix, including final demand.

9.6.4 Transport to energy conversion site

		1	2
1: Transport to conversion site	tkm		0,001
2: Dummy	MJ		

Table 71: foreground system for the transport to energy conversion site step.

9.6.5 Energy conversion

		1	2	3	4	5	6	7	8	9	10
1: Pre-treatment choice	MJ			1							
2: Combustion emissions	MJ			1							
3: MJ fuel to operation	MJ						1,11				
4: CHP infrastructure	p						1,41E-11				
5: Wood ash to landfilling	kg						1,17E-02				
6: Operation	MJ useful							1			
7: Allocation	MJ/MJ								3,6	3,6	
8: Electricity	kWh										1
9: Heat	kWh										0
10: Dummy CHP, el	kWh										

Table 72: CHP, electricity part of the energy conversion foreground matrix. Identical for clean and waste wood options.

		1	2	3	4	5	6	7	8	9	10
1: Pre-treatment choice	MJ			1							
2: Combustion emissions	MJ			1							
3: MJ fuel to operation	MJ						1,11				
4: CHP infrastructure	p						2,82E-11				
5: Wood ash to landfilling	kg						1,17E-02				
6: Operation	MJ useful							1			
7: Allocation	MJ/MJ								3,6	3,6	
8: Electricity	kWh										0
9: Heat	kWh										1
10: Dummy CHP, heat	kWh										

Table 73: CHP, heat part of the conversion foreground matrix. Identical for clean and waste wood options.

		1	2	3	4	5	6	7	8
1: Pre-treatment choice	MJ			1					
2: Combustion emissions	MJ			1					
3: MJ fuel to operation	MJ						2,50		
4: Infrastructure	p						1,69E-11		
5: Wood ash to landfilling	kg						2,63E-02		
6: Operation	MJ useful							3,6	
7: Electricity	kWh								1
8: Dummy thermal, el	kWh								

Table 74: thermal, electricity part of the conversion foreground matrix. Identical for clean and waste wood options.

		1	2	3	4	5	6	7	8
1: Pre-treatment choice	MJ			1					
2: Combustion emissions	MJ			1					
3: MJ fuel to operation	MJ						1,16		
4: Infrastructure	p						3,64E-11		
5: Wood ash to landfilling	kg						1,22E-02		
6: Operation	MJ useful							3,6	
7: Heat	kWh								1
8: Dummy DH, heat	kWh								

Table 75: district heating part of the conversion foreground matrix. Identical for clean and waste wood options.

		1	2	3	4	5	6	7	8
1: Pre-treatment choice	MJ			1					
2: Combustion emissions	MJ			1					
3: MJ fuel to operation	MJ						1,12		
4: Infrastructure	p						3,76E-11		
5: Wood ash to landfilling	kg						1,18E-02		
6: Operation	MJ useful							3,6	
7: Heat	kWh								1
8: Dummy boiler, steam	kWh								

Table 76: Boiler, steam part of the conversion foreground matrix. Identical for clean and waste wood options.

Dummys		**y_f:**	1	2	3	4	5	6	7	8	9	10	11
1: CHP, el, clean wood	kWh												0
2: CHP, el waste wood	kWh												0
3: CHP, heat, clean wood	kWh												0
4: CHP, heat, waste wood	kWh												0

5: Thermal, el, clean wood	kWh												0
6: Thermal, el, waste wood	kWh												0
7: DH, heat, clean wood	kWh												0
8: DH, heat, waste wood	kWh												0
9: boiler, steam, clean wood	kWh												0
10: Boiler, steam, waste wood	kWh												0
11: Dummy choice	kWh	1											

Table 77: final part of the energy conversion foreground matrix, including the final demand.

9.6.6 Distribution

		y_f:	1	2	3	4	5	6	7	8
1: Conversion choice	kWh			1,15	1,14	1,14				
2: Electricity to end user	kWh						1			
3:Heat to end user	kWh							1		
4: Steam to end user	kWh								1	
5: Dummy electricity to end user	kWh									0
6: Dummy heat to end user	kWh									0
7: Dummy steam to end user	kWh									0
8: Dummy choice	kWh	1								

Table 78: foreground matrix and final demand vector for the energy distribution step.

9.7 Appendix 7: Matlab script

Two Matlab scripts are used for the calculations; one loading and initialising the templates, and one performing the calculations. See

---

Table 50 and Table 51 respectively.

```
%loading templates
%first step is to run the templates in Arda and export the
foreground as a mat file
%save as follows:
%LCA_foreground_enduse.mat
%LCA_foreground_conv.mat
%LCA_foreground_treat.mat
%LCA_foreground_feed.mat
%LCA_foreground_t_feed.mat
%LCA_foregound_t_treat.mat

%second step: once first step is completed then run this
script:

disp('starting loading templates')

clear all
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_enduse.mat'
A_enduse = [A_ff A_fb; A_bf A_gen];
F_enduse = [F_f F_gen];
yf_size_enduse = size(y_f,1);
PRO_f_enduse=PRO_f;
save A_F_enduse.mat
clear
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_conv.mat'
A_conv = [A_ff A_fb; A_bf A_gen];
F_conv = [F_f F_gen];
yf_size_conv = size(y_f,1);
PRO_f_conv =PRO_f;
save A_F_conv.mat
clear
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_treat.mat'
A_treat = [A_ff A_fb; A_bf A_gen];
F_treat = [F_f F_gen];
yf_size_treat = size(y_f,1);
PRO_f_treat =PRO_f;
save A_F_treat.mat
```

```
clear
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_feed.mat'
A_feed = [A_ff A_fb; A_bf A_gen];
F_feed = [F_f F_gen];
yf_size_feed = size(y_f,1);
PRO_f_feed =PRO_f;
save A_F_feed.mat
clear
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_t_feed.mat'
A_t_feed = [A_ff A_fb; A_bf A_gen];
F_t_feed = [F_f F_gen];
yf_size_t_feed = size(y_f,1);
PRO_f_t_feed =PRO_f;
save A_F_t_feed.mat
clear
load 'Ecoinvent_2_2_database.mat'
load 'LCA_Foreground_t_treat.mat'
A_t_treat = [A_ff A_fb; A_bf A_gen];
F_t_treat = [F_f F_gen];
yf_size_t_treat = size(y_f,1);
PRO_f_t_treat =PRO_f;
save A_F_t_treat.mat
clear
%read in trans_treat, trans_feed and dense_feed vectors
trans_treat = xlsread('Transport to conversion site
template.xls','trans_treat','f8:f77'); %kg-km/MJ (e8=SR/TOP-
steam ww...e60=chips-CHPelec cw)
trans_feed = xlsread('Transport to pre-treatment site
template.xls', 'trans_feed', 'f7:f48'); %kg-km-m3 (e7=ww-SR
direct...e42=stemwood-chipping)
dense_feed = xlsread('Feedstock template.xls', 'dens_feed',
'd4:d9'); %wet densities of feedstock kg/m3
(d4=stemwood...d9=con/dem waste)
save vectors.mat
clear

disp('finished loading templates')
```

Table 79: Matlab script loading the templates.

```
disp('starting LCA calculations')

%%basic LCA calculations for the possible combinations of
value chains
```

```
clear all

%load vectors and matrices
load A_F_enduse.mat;load A_F_conv.mat; load A_F_treat.mat;load
A_F_feed.mat; load  A_F_t_feed.mat; load A_F_t_treat.mat;load
Ecoinvent_2_2_database.mat; load vectors;

%initalize y,x,d and I vectors
y_enduse = zeros((size(A_enduse,1)),1);
x_enduse = zeros((size(A_enduse,1)),1);
I_enduse = eye(size(y_enduse,1));
d_enduse = zeros(size(C,1),1);
y_conv = zeros((size(A_conv,1)),1);
x_conv = zeros((size(A_conv,1)),1);
I_conv = eye(size(y_conv,1));
d_conv = zeros(size(C,1),1);
y_treat = zeros((size(A_treat,1)),1);
x_treat = zeros((size(A_treat,1)),1);
I_treat = eye(size(y_treat,1));
d_treat = zeros(size(C,1),1);
y_feed = zeros((size(A_feed,1)),1);
x_feed = zeros((size(A_feed,1)),1);
I_feed = eye(size(y_feed,1));
d_feed = zeros(size(C,1),1);
y_t_feed = zeros((size(A_t_feed,1)),1);
x_t_feed = zeros((size(A_t_feed,1)),1);
I_t_feed = eye(size(y_t_feed,1));
d_t_feed = zeros(size(C,1),1);
y_t_treat = zeros((size(A_t_treat,1)),1);
x_t_treat = zeros((size(A_t_treat,1)),1);
I_t_treat = eye(size(y_t_treat,1));
d_t_treat = zeros(size(C,1),1);

value_chain = zeros(1,7); %this will become a matrix of every
feasible combination of enduse, conversion, treated transport,
treatment, feed stock transport and feedstock.
D_pro_value_chains = zeros(55,6); %this will become a matrix
of the advanced contribution analysis results for all impact
categories for every combination of enduse, conversion,
treated transport, treatment, feed stock transport and
feedstock.
bioCO2_value_chains = zeros(2,6); %this will become a vector
of the advanced contribution analysis results for bioCO2
emission for every combination of enduse, conversion, treated
transport, treatment, feed stock transport and feedstock.
n = 1; %a counter for each combination of fuel chain
f = 1; %a counter to know which feedstock has been chosen ((1)
construction/demolition waste, (2) pap/cardboard, (3) saw
residues, (4) energywood, (5) FR, (6)stemwood)
c = 1; %a counter to know which energy service is being
produced

for enduse = 1:3 %number of enduse services (steam (1), space
heating (2) and power (3)) skal stå 1:3
    y_enduse = y_enduse*0;
```

```
    y_enduse((yf_size_enduse-enduse),1) = 1;
    x_enduse = (I_enduse-A_enduse)^-1*y_enduse; %cont LCA
calcs etc...
    d_enduse = C*F_enduse*x_enduse;
    e_bioCO2_enduse = ones(1,3)*F_enduse(108:110,:)*x_enduse;
%returns a 1x1 of kg bio CO2 emissions

    for conv = 1:10 % skal stå 1:10 number of conversion
options ((1)steam-ww; 2)steam-cw; 3)dh-ww; 4)dh-cw; 5)therm-
elec-ww;6)therm-elec-cw;7)chp-heat-ww;8)chp-heat-cw;9)chp-
elec-ww;10)chp-elec-cw)
        %eliminating unfeasible conversion to enduse options
        if enduse ==1 && conv == 3 || enduse ==1 && conv == 4
||enduse ==1 && conv == 5 ||enduse ==1 && conv == 6 || enduse
==1 && conv == 7 || enduse ==1 && conv == 8 || enduse ==1 &&
conv == 9 || enduse ==1 && conv == 10
            continue
        end
        if enduse ==2 && conv == 1 || enduse ==2 && conv == 2
||enduse ==2 && conv == 5 ||enduse == 2 && conv == 6 || enduse
==2 && conv == 9 || enduse ==2 && conv == 10
            continue
        end
        if enduse ==3 && conv == 1 || enduse ==3 && conv == 2
||enduse ==3 && conv == 3 ||enduse == 3 && conv == 4 || enduse
==3 && conv == 7 || enduse ==3 && conv == 8
            continue
        end

        y_conv = y_conv*0;
        y_conv((yf_size_conv-conv),1) = x_enduse(1,1);
%chooses the output of useful energy at plant required to
produce y_enduse(1,enduse)
        x_conv = (I_conv - A_conv)^-1*y_conv; % cont LCA calcs
etc...
        d_conv = C*F_conv*x_conv;
        e_bioCO2_conv = ones(1,3)*F_conv(108:110,:)*x_conv;
%returns a 1x1 of kg bio CO2 emissions

        for treat = 1:7 %skal stå 1:7 number of treatment
options ((1) chipping, (2) chipping/pelletization, (3) cw
TOP:chipping/torrefied pellets, (4) ww TOP:chipping/torrefied
pellets, (5) SR direct, (6) SR pelletization, (7) SR torrefied
pellets)
            y_treat = y_treat*0;
            y_treat((yf_size_treat-8+treat),1) = x_conv(1,1);
%chooses the output of treated fuel at entry to plant required
to produce y_conv(1,conv)
            x_treat = (I_treat - A_treat)^-1*y_treat; %cont
LCA calcs etc...
            d_treat = C*F_treat*x_treat;
            e_bioCO2_treat =
ones(1,3)*F_treat(108:110,:)*x_treat; %returns a 1x1 of kg bio
CO2 emissions
```

```
            for feed = 1:6 % skal stå 1:6 number of feedstocks
that differ in terms of inputs required from the technosphere
((1) construction/demolition waste, (2) pap/cardboard, (3) saw
residues, (4) energywood, (5) FR, (6)stemwood)
                %eliminating unfeasible feed stock to
treatment and feedstock to conversion optoins
                if treat == 1 && feed == 3  %removing feed
stocks that cannot be chipped
                    continue
                end
                if treat == 2 && feed == 2 || treat  == 2 &&
feed == 3  %removing feed stocks that cannot be
chipped/pelletized
                    continue
                end
                if treat == 3 && feed == 2 || treat  == 3 &&
feed == 3 || treat ==3 && feed == 1 %removing feed stocks that
cannot be chipped/TOPed and are not cw
                    continue
                end
                if treat == 4 && feed == 2 || treat  == 4 &&
feed == 3 || treat ==4 && feed == 4 || treat ==4 && feed == 5
|| treat ==4 && feed == 6   %removing feed stocks that cannot
be chipped/TOPed and are not ww
                    continue
                end
                if treat == 5 && feed == 1 || treat  == 5  &&
feed == 2 || treat  == 5  && feed == 4 || treat == 5  && feed
== 5 || treat  == 5  && feed == 6 %removing non saw residue
feedstocks
                    continue
                end
                if treat == 6 && feed == 1 || treat  == 6  &&
feed == 2 || treat  == 6   && feed == 4 || treat  == 6  &&
feed == 5 || treat == 6  && feed == 6 %removing non saw
residue feedstocks
                    continue
                end
                if treat == 7 && feed == 1 || treat  == 7  &&
feed == 2 || treat  == 7  && feed == 4 || treat  == 7  && feed
== 5 || treat == 7  && feed == 6 %removing non saw residue
feedstocks
                    continue
                end
                if conv == 1 && feed == 3 || conv == 1 && feed
== 4 ||conv == 1 && feed == 5 ||conv == 1 && feed == 6
%removing non-contaminated biomass streams for steam ww
                    continue
                end
                if conv == 2 && feed == 1 || conv == 2 && feed
== 2   %removing contaminated biomass streams for steam cw
                    continue
                end
```

```
                if conv == 3 && feed == 3 || conv == 3 && feed
== 4 ||conv == 3 && feed == 5 ||conv == 3 && feed == 6
%removing non-contaminated biomass streams for dh ww
                    continue
                end
                if conv == 4 && feed == 1 || conv == 4 && feed
== 2   %removing contaminated biomass streams for dh cw
                    continue
                end
                if conv == 5 && feed == 3 || conv == 5 && feed
== 4 ||conv == 5 && feed == 5 ||conv == 5 && feed == 6
%removing non-contaminated biomass streams for therm elec ww
                    continue
                end
                if conv == 6 && feed == 1 || conv == 6 && feed
== 2   %removing contaminated biomass streams for thermal
power cw
                    continue
                end
                if conv == 7 && feed == 3 || conv == 7 && feed
== 4 ||conv == 7 && feed == 5 ||conv == 7 && feed == 6
%removing non-contaminated biomass streams for chp dh ww
                    continue
                end
                if conv == 8 && feed == 1 || conv == 8 && feed
== 2   %removing contaminated biomass streams for chp heat cw
                    continue
                end
                if conv == 9 && feed == 3 || conv == 9 && feed
== 4 ||conv == 9 && feed == 5 ||conv == 9 && feed == 6
%removing non-contaminated biomass streams for chp elec ww
                    continue
                end
                if conv == 10 && feed == 1 || conv == 10 &&
feed == 2   %removing contaminated biomass streams for chp-
power cw
                    continue
                end


                y_feed = y_feed*0;
                y_feed((yf_size_feed-feed),1) = x_treat(1,1);
%chooses the output of feed stock at entry to treatment plant
required to proudce y_treat(1,treat)-dense_feed converts from
kg to m3;
                x_feed = (I_feed - A_feed)^-1*y_feed;
                d_feed = C*F_feed*x_feed;
                e_bioCO2_feed =
ones(1,3)*F_feed(108:110,:)*x_feed; %returns a 1x1 of kg bio
CO2 emissions

                for t_treat = 1  %number of transport options
for transporting the treated biomass  (large lorry)
                    y_t_treat = y_t_treat*0;
```

```
                    y_t_treat((yf_size_t_treat+1-t_treat),1)=
trans_treat((7-treat+1)*10-(10-
conv),1)*y_treat((yf_size_treat-8+treat),1); %trans_treat is a
(treat*conv)*1 vector of distances in tkm/x_conv to transport
the treated biomass from treatment facility to conversion
plant
                    x_t_treat= (I_t_treat-A_t_treat)^-
1*y_t_treat;
                    d_t_treat = C*F_t_treat*x_t_treat;
                    e_bioCO2_t_treat =
ones(1,3)*F_t_treat(108:110,:)*x_t_treat; %returns a 1x1 of kg
bio CO2 emissions

                    for t_feed = 1  %number of transport
options for transporting the feedstock  (large lorry)
                        y_t_feed = y_t_feed*0;
                        y_t_feed((yf_size_t_feed+1-
t_feed),1)=trans_feed(feed*7-(treat-
1),1)*y_feed((yf_size_feed-feed),1); %trans_feed is a
(feed*treat)*1 vector of distances in tkm/x_treat(1,1) to
transport the feed stock from edge of resource pool to
treatment plant
                        x_t_feed = (I_t_feed-A_t_feed)^-
1*y_t_feed;
                        d_t_feed = C*F_t_feed*x_t_feed;
                        e_bioCO2_t_feed =
ones(1,3)*F_t_feed(108:110,:)*x_t_feed; %returns a 1x1 of kg
bio CO2 emissions
                        %could put in some if statements here
where emission factors differ because of the feedstock type

                        %storing the advanced contribution
analysis of each system; in this case we have four forground
processes: energy distribution, energy conversion, biomass
treatment, feedstock procurement
                        %it may be worth further
disaggregation; if so i think it would be easiest to make more
templates where each template represents a part of the value
chain as this coding assumes.
                        %Other foregroun processes of interest
include: transportation of treated biomass, road transport of
untreated biomass, forestry operation. that would mean just
three more templates.

                        D_pro_value_chains(:,1+(n-1)*6:(n-
1)*6+6) = [feed,t_feed,treat,t_treat,conv,enduse;
d_feed,d_t_feed d_treat, d_t_treat,d_conv,d_enduse]; %every
six columns will show the advanced contribution of a single
combination
                        bioCO2_value_chains(:,1+(n-1)*6:(n-
1)*6+6) = [feed,t_feed,treat,t_treat,conv,enduse;
e_bioCO2_feed,e_bioCO2_t_feed,e_bioCO2_treat,e_bioCO2_t_treat,
e_bioCO2_conv,e_bioCO2_enduse]; %every six columns will show
the advanced contribution of a single combination
```

```
                        %storing the combinations in
value_chain matrix
                        value_chain(n,1) = n;
                        value_chain(n,2) = feed;
                        value_chain(n,3) = t_feed;
                        value_chain(n,4) = treat;
                        value_chain(n,5) = t_treat;
                        value_chain(n,6) = conv;
                        value_chain(n,7) = enduse;

                        n=n+1

                    end
                end
            end
        end
    end
end



%%writing results to excel
D_pro_midH_value_chains = D_pro_value_chains(19:36, :);
trnsp_D_pro_midH_value_chains = D_pro_midH_value_chains';
D_tot =zeros(19,150);
transp_bioCO2 = bioCO2_value_chains(2,:)';
BIOCO2_tot = zeros(1,100);
for i = 1:n-1
    D_tot(1,i) =i;
    d_tot = sum(trnsp_D_pro_midH_value_chains(1+(i-1)*6:(i-
1)*6+6,:));
    D_tot(2:19,i) = d_tot';
    bioCO2_tot = sum(transp_bioCO2(1+(i-1)*6:(i-1)*6+6,:));
    BIOCO2_tot(1,i) = bioCO2_tot';
end

d_lables = IMP(19:36,1:7);

disp('finished LCA calculations')
```

Table 80: Matlab script performing LCA calculations.

9.8 Appendix 8: feasible value chain combinations

n	Feedstock	Treatment	Conversion	Enduse
1	Wood waste	Chipping	Steam, ww	Steam
2	P&C waste	Chipping	Steam, ww	Steam
3	Wood waste	Pelletising	Steam, ww	Steam
4	Wood waste	TOP ww	steam-ww	Steam
5	Energy wood	Chipping	Steam, cw	Steam
6	FR	Chipping	Steam, cw	Steam
7	Stemwood	Chipping	Steam, cw	Steam
8	Energy wood	Pelletising	Steam, cw	Steam
9	FR	Pelletising	Steam, cw	Steam
10	Stemwood	Pelletising	Steam, cw	Steam
11	Energy wood	TOP cw	Steam, cw	Steam
12	FR	TOP cw	Steam, cw	Steam
13	Stemwood	TOP cw	Steam, cw	Steam
14	SR	SR direct	Steam, cw	Steam
15	SR	SR pelletising	Steam, cw	Steam
16	SR	SR TOP cw	Steam, cw	Steam
17	Wood waste	Chipping	DH, ww	Heat
18	P&C waste	Chipping	DH, ww	Heat
19	Wood waste	Pelletising	DH, ww	Heat
20	Wood waste	TOP ww	DH, ww	Heat
21	Energy wood	Chipping	DH, cw	Heat
22	FR	Chipping	DH, cw	Heat
23	Stemwood	Chipping	DH, cw	Heat
24	Energy wood	Pelletising	DH, cw	Heat
25	FR	Pelletising	DH, cw	Heat
26	Stemwood	Pelletising	DH, cw	Heat
27	Energy wood	TOP cw	DH, cw	Heat
28	FR	TOP cw	DH, cw	Heat
29	Stemwood	TOP cw	DH, cw	Heat
30	SR	SR direct	DH, cw	Heat
31	SR	SR pelletising	DH, cw	Heat
32	SR	SR TOP cw	DH, cw	Heat
33	Wood waste	Chipping	CHP, heat, ww	Heat
34	P&C waste	Chipping	CHP, heat, ww	Heat
35	Wood waste	Pelletising	CHP, heat, ww	Heat
36	Wood waste	TOP ww	CHP, heat, ww	Heat
37	Energy wood	Chipping	CHP, heat, cw	Heat
38	FR	Chipping	CHP, heat, cw	Heat
39	Stemwood	Chipping	CHP, heat, cw	Heat

40	Energy wood	Pelletising	CHP, heat, cw	Heat
41	FR	Pelletising	CHP, heat, cw	Heat
42	Stemwood	Pelletising	CHP, heat, cw	Heat
43	Energy wood	TOP cw	CHP, heat, cw	Heat
44	FR	TOP cw	CHP, heat, cw	Heat
45	Stemwood	TOP cw	CHP, heat, cw	Heat
46	SR	SR direct	CHP, heat, cw	Heat
47	SR	SR pelletising	CHP, heat, cw	Heat
50	SR	SR TOP cw	CHP, heat, cw	Heat
49	Wood waste	Chipping	therm-elec-ww	Electricity
50	P&C waste	Chipping	therm-elec-ww	Electricity
51	Wood waste	Pelletising	therm-elec-ww	Electricity
52	Wood waste	TOP ww	therm-elec-ww	Electricity
53	Energy wood	Chipping	therm-elec-cw	Electricity
54	FR	Chipping	therm-elec-cw	Electricity
55	Stemwood	Chipping	therm-elec-cw	Electricity
56	Energy wood	Pelletising	therm-elec-cw	Electricity
57	FR	Pelletising	therm-elec-cw	Electricity
58	Stemwood	Pelletising	therm-elec-cw	Electricity
59	Energy wood	TOP cw	therm-elec-cw	Electricity
60	FR	TOP cw	therm-elec-cw	Electricity
61	Stemwood	TOP cw	therm-elec-cw	Electricity
62	SR	SR direct	therm-elec-cw	Electricity
63	SR	SR pelletising	therm-elec-cw	Electricity
64	SR	SR TOP cw	therm-elec-cw	Electricity
65	Wood waste	Chipping	CHP, el, ww	Electricity
66	P&C waste	Chipping	CHP, el, ww	Electricity
67	Wood waste	Pelletising	CHP, el, ww	Electricity
68	Wood waste	TOP ww	CHP, el, ww	Electricity
69	Energy wood	Chipping	CHP, el, cw	Electricity
70	FR	Chipping	CHP, el, cw	Electricity
71	Stemwood	Chipping	CHP, el, cw	Electricity
72	Energy wood	Pelletising	CHP, el, cw	Electricity
73	FR	Pelletising	CHP, el, cw	Electricity
74	Stemwood	Pelletising	CHP, el, cw	Electricity
75	Energy wood	TOP cw	CHP, el, cw	Electricity
76	FR	TOP cw	CHP, el, cw	Electricity
77	Stemwood	TOP cw	CHP, el, cw	Electricity
78	SR	SR direct	CHP, el, cw	Electricity
79	SR	SR pelletising	CHP, el, cw	Electricity
80	SR	SR TOP cw	CHP, el, cw	Electricity

Table 81: feasible value chain combinations.3