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Environmental Assessment of Scenarios for Products and Services based on Forest Resources in Norway

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PREFACE

This master thesis is submitted in partial fulfillment of the requirements for the Master of Science degree at the Norwegian University of Science and Technology (NTNU). The underlying work has been carried out at the Department of Energy and Process Engineering, as a part of the activities within the Bioenergy Innovation Centre (CenBio).

CenBio is one of Norway's Centres for Environment-friendly Energy Research (CEER), co-funded by the Norwegian Research Council. The intention of the CEER scheme is to establish time-limited research centres with concentrated research on specific fields within environmentally friendly energy. The Norwegian University of Life Sciences (UMB) is the host institution for CenBio, while SINTEF Energi AS is the centre leader. The overall objective of CenBio is to develop the basis for a sustainable and cost-effective bioenergy industry in Norway, in order to achieve the national goal of doubling bioenergy use by 2020. To reach this objective, CenBio will address the entire value chains of virgin biomass and biodegradable waste fractions, including their production, harvesting and transportation, conversion processes and the handling of residues. This master thesis attempts to give valuable information on these value chains in an environmental system analysis context.

I would like to thank my supervisors, Anders Hammer Strømman and Ottar Michelsen (co-supervisor during the fall 2010), for their inspiring enthusiasm and valuable guidance throughout the project.

Trondheim, June 2011.

Magnus Grinde

SUMMARY

Energy from wood biomass is one of the prioritized areas of focus in current Norwegian energy politics. The prevailing perception of bioenergy is that it is climate neutral, making this strategy appear to be an effective measure in combating climate change. Furthermore, bioenergy is considered to be relatively source of energy, and steadily increasing Norwegian forests imply huge amounts of wood available. However, not all of this wood is easily accessible with current technology and market situations (i.e. prices). As wood also is used for many other purposes, mainly construction and paper production, the bioenergy industry will have to compete with these other industries for the access to raw materials.

A change in current utilization of our wood resources is in this thesis assessed in an environmental perspective in order to better understand how such a shift would influence the overall environmental impacts. First, a wood flow mapping of the current (2006) situation was carried out and applied in a 'hybrid life cycle assessment' model utilizing life cycle inventories which represent the industries within the Norwegian wood products sector. Then, an alternative wood flow scenario where more wood were used for bioenergy purposes, at the expense of reduced domestic paper- and wood panel production, was studied.

Besides from being highly representative for Norwegian conditions, the model was developed with the intention of being able to show the breakdown of environmental impacts for both for entire sector as well as for specific products and industries. Furthermore, in contrast to the current dominant perception, recent research has pointed to the fact that the resulting greenhouse gas emissions from combustion of biomass will have a significant climate change impact even if new biomass is replanted immediately, as the gases will spend a considerable time in the atmosphere before being absorbed. This new insight may seriously influence the perceived effectiveness of bioenergy in climate change mitigation efforts. Consequently, it was considered valuable to include estimated climate change impact potentials of biogenic carbon emissions (CO_2 and CH_4) in this assessment.

Although the developed model probably should be further refined before ultimate conclusions are made based on the assessment results, some important observations can be commented. First of all, it was clearly shown that whether or not climate change impacts from biogenic

carbon emissions are considered is highly relevant to the overall climate change mitigation effect of bioenergy. Still, even when these are included there are considerable environmental gains when e.g. substituting fossil energy with wood-based bioenergy.

Secondly, the results illustrate how impacts from different environmental impact categories are distributed within the wood products sector (pulp & paper production clearly being the dominant industry), within the products' value chains and for the overall system (characterized by the impacts from paper- and heat production as well as the use of transportation fuels).

SAMMENDRAG

Trebasert bioenergi er ett av satsingsområdene i dagens norske energipolitikk. Den rådende oppfatning er at bioenergi er en klimanøytral energiform, noe som gjør denne satsingen tilsynelatende er et effektivt tiltak i kampen mot globale klimaendringer. Dessuten oppfattes bioenergi som en relativt billig energikilde, og stadig økende norske skogsvolum innebærer et enormt ressurspotensial. På den annen side er ikke alle disse ressursene like lett tilgjengelig med nåværende teknologi og markedssituasjon (dvs. priser). Siden tre også blir benyttet til mange andre formål, hovedsaklig byggmaterialer og papir, betyr det at bioenergiindustrien vil måtte konkurrere med andre aktører om tilgangen på råmaterialer.

I denne masteroppgaven studeres hvordan en endring i nåværende utnyttelse av de totale treressursene vil slå ut med tanke på ulike miljøkonsekvenser. Aller først ble en kartlegging av de norske trestrømmene i 2006 gjennomført. Denne informasjonen blir deretter benyttet i en såkalt 'hybrid livssyklusvurdering' modell som er satt sammen av livssyklus data som er representative for de norske treprodukt industriene. Etter en gjennomgang av modellen blir det presentert et alternativt scenario for utnyttelse av de norske treressursene hvor mer tre blir brukt til bioenergi formål på bekostning av redusert norsk produksjon av papir og treplater..

I tillegg til å være svært representativ for norske forhold, ble modellen utviklet med den hensikt å kunne vise den respektive fordeling av miljøeffekter for hele sektoren, men også for spesifikke produkter og industrier. Dessuten har nyere forskning, i kontrast til dagens dominerende oppfattning, påpekt at klimagassutslippene fra biomasse forbrenning vil ha en signifikant effekt i et globalt oppvarmingsperspektiv selv om man antar at nye biomasse blir plantet umiddelbart. Ettersom mesteparten av de resulterende klimagassene fra forbrenningsprosessen vil tilbringe betydelig tid i atmosfæren før de blir absorbert av den nye biomassen vil de altså ha en effekt på den globale oppvarming. Denne nye innsikten kan få store konsekvenser for hvordan vi oppfatter bioenergi i et klimaperspektiv. Derfor var det vurdert som verdifullt å inkludere dette aspektet i analysen utført her.

Selv om den konstruerte modellen antagelig burde finpusses ytterligere før endelige konklusjoner blir gjort på bakgrunn av analyse resultatene, kan man observere noen viktige tendenser i resultat materialet. For det første kom det tydelig fram at hvorvidt man velger å

inkludere klimaeffekten av CO_2 og CH_4 utslipp fra biomasse er svært relevant for bioenergi sitt totale klimagass reduksjonspotensialet, men uansett vil en utskifting av fossile energikilder med trebasert bioenergi i de aller fleste tilfeller medføre store miljømessige fordeler.

Dessuten gir resultatene et godt innblikk i hvordan de ulike miljøkonsekvensene fordeler seg innenfor treprodukt sektoren (hvor papirindustrien er den dominerende industrien), innenfor produktene sine verdikjeder og for hele systemet (hvor de viktigste kildene er utslipp fra papir- og varme produksjon i tillegg til utslipp i forbindelse med bruk av transport drivstoff).

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1 INTRODUCTION

1.1 Motivation

A combination of several factors such as diminishing fossil energy resources, an ever increasing global demand for energy and various environmental issues, climate change in particular, are forcing us to establish a more sustainable energy system for the future. Bioenergy is widely acknowledged as one of the preferred alternatives to fossil energy, and is expected to constitute a significant part of the future energy mix. Unfortunately, some of the previous strategies to utilize biomass for energy purposes have suffered from incomplete environmental assessments. The most obvious example of this is that of first generation biofuels (e.g. bioetahnol from sugar or biodiesel from rape seeds) which has been one of the focus areas within bioenergy up until now. Encouraged by research indicating that biofuels could provide substantial, relatively cheap, energy while mitigating climate change, governments have over the last decades supported production aimed at increasing biofuel use in many countries. However, in recent years concern has been increasing about negative implications of growing biomass for biofuel production. This concern includes the food-versus-fuel conflict, biodiversity impacts and land use changes with subsequent climate change impacts. The controversy around first generation biofuels has clearly indicated the need for holistic and complete environmental assessments of new energy policies, in order to identify the most effective policies before investments in technology and infrastructure are made.

As one of the countries that have made a huge profit on the fossil energy era, Norway is now aiming to be a pioneer country in climate change mitigation and promotion of renewable energy technologies. The oil & gas industry is today the largest industry in Norway, but due to expectations of declining activity in the years to come we need to plan for the future by establishing new industries. Fortunately, Norway is also blessed with large amounts of renewable energy resources such as hydro-, wind-, wave- and bioenergy. Consequently, there is no reason why the energy sector shouldn't remain an important sector in the Norwegian economy in the future as well. In the case of bioenergy, huge amounts of biomass can be found in the Norwegian forests. Current harvest levels are much below annual growth, and in 2005 the net growth was estimated to approximately 15 million cubic metres (Bernhard and

Bugge, 2006, p.1). While the current energy production based on biomass in Norway is about 14 TWh, or 10% of the stationary energy consumption (Trømborg et al., 2008), the national target is to reach 28 TWh by 2020, i.e. a doubling of current production (Berthelsen, 2010).

However, Norway also has other industries that apply wood as raw material. The domestic industries producing timber, wooden boards, pulp and paper are all significant industries with a long history and established infrastructure. Today, only the lower grade trees and forest-/industrial residues are directly utilized for bioenergy purposes. If we neglect the possibility to increase overall annual harvest levels, i.e. assume that they are kept approximately fixed, it becomes clear that producers of bio fuels would have to compete even harder with the established industries for the access to raw materials (i.e. wood) if the total production of bioenergy is to increase. In order to deal with this competition the bioenergy industry would probably depend on new policies which in some way increased their competitive ability (e.g. substitutes, measures to stimulate higher energy prices, etc). On the other hand, increased domestic production of bioenergy would then imply decreased domestic production of something else (e.g. paper) which would have to be produced elsewhere in the world in order to saturate global demand. The question that arises is whether the benefits, as seen from a 'global perspective',[1] of having a higher share of bioenergy in Norway outweigh the potential drawbacks of producing e.g. paper somewhere else. In order to identify the 'best' way to utilize a resource, different analytical tools are needed in order to cover various aspects such as economics, environmental concerns, socials issues, etc. When only considering the environmental aspect the question above can be rephrased as: how should we best make use of the Norwegian forest resources when considering environmental impacts on a global level?

Life Cycle Assessment (LCA) is the state-of-the-art tool for holistic environmental assessments. Traditional, process-based LCA is generally considered to have a good level of detail, but sometimes suffers in lack of completeness due to inadequate system boundaries (Strømman, 2008, p.92). Input-Output Analysis (IOA), on the other hand, has the opposite characteristics. In recent years, the idea of 'hybrid life cycle assessment' has gained increasingly higher recognition as it combines the respective strengths of process-based LCA (i.e. high level of detail) and IOA (i.e. comprehensive system boundaries). Since many of the

[1] By a 'global perspective' it is meant that decisions are made based on what is best for the world, not e.g. what would be best for only Norway in terms of fulfilling the Kyoto agreement where only emissions actually occuring within a country's boarders are considered

processes in the forest- and wood industries deliver multiple outputs, allocation of impacts onto each output is necessary in order to achieve results representative for the actual situation. This promotes the need for a systematic overview of the flows of wood-based products within the sector. As this project work was initiated, it quickly became clear that there had been little previous efforts on establishing an overview of these flows in Norway.[2] Therefore, this became an important part of the work carried out during my project.

1.2 State-of-the-art

Regarding comprehensive mappings of wood product flows in Norway, there exist to the author's knowledge no complete official statistics as of this date. However, as a part of the UNECE Timber Committee's Joint Wood for Energy Enquiry (JWEE) project, Statistics Norway is in the process of establishing an overview similar to the one described in this report. The aim of the Joint Wood Energy Questionnaire is to provide policy makers with more precise information on the national/regional level on (United Nations Economic Commission for Europe, 2010):

- ✓ Roundwood equivalent used for energy production
- ✓ Sources for wood energy production (direct/indirect/post consumer)
- ✓ Wood energy's share of national/regional energy/bioenergy production.
- ✓ Consumers of wood energy

Unfortunately, Statistics Norway's JWEE tables are still incomplete due to lack of resources, but according to their head representative on the project, Trond A. Steinset, they are hoping to complete the tables (and have the resources to update them) within 2011.

The Norwegian University of Life Sciences has also done some work on establishing wood flow mappings in Norway. Although not easily accessible to the public, some of this data is implemented in the Norwegian Trade Model II (NTM II) which is an economic equilibrium model for the Norwegian wood- and forestry industry, developed by researchers at the

[2] Although the master thesis ”*Logs, wood based products and pulp & paper products in Norway – product flows and value added in the wood based value chain*” by Rødland, K.A. (2009) contained many of the most important flows, considerable modifications and additions were needed in order to fulfill the requirements of the LCA- and IOA framework.

university. Secondly, estimates on many of the most important wood flows are presented in a master thesis from 2009 by Kjetil André Rødland. That master thesis has provided the main data basis for the work performed on wood flow mapping in this study. However, as Rødland's thesis was not carried out with the direct intention of utilization within environmental assessments, the need for a mapping suited for such purposes is still present. Consequently, a considerable amount of modifications and additional data collection were required throughout this project work.

When it comes to environmental assessments of wood products, the Norwegian research project MIKADO has during the last years made some important contributions to the field. MIKADO was a co-operation between the industry, major research institutions and public funding institutions, and was lead by SINTEF Building and Infrastructure. It lasted from 2007 until 2009 and the main objective was to raise awareness on the environmental performance of wood based products, and thereby increase their competitive ability. The project produced several life cycle assessments, Environmental Product Declarations (EPD) and other publications that can be found on the projects homepage.[3] Currently, MIKADO's successor KlimaTre is starting up with a time horizon of four additional years. Within KlimaTre, the focus is expanded to include macroeconomic aspects of the wood value chains and some relevant publications for this field are posted on this project's webpage.[4] Although neither research projects focus particularly on biofuels, the life cycle inventories (LCI) developed during the research can be useful for any kind of environmental assessment concerning Norwegian wood products.

For the case of second generation wood-based bioetanol, a Norwegian specific LCA has been carried out here at the Department of Energy and Process Engineering, NTNU (Bright, et al., 2009a). This assessment is based on a detailed life cycle inventory for the value chain of bioethanol production in Norway, and has provide valuable information for this product category in this assessment as well.

At last, the report "*Miljøeffekter ved bruk av tre - Sammenstilling av kunnskap om tre og treprodukter*" (Flæte et al., 2008) gives a comprehensive overview of LCAs performed within wood products applications in the building industry.

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3 http://www.sintef.no/Projectweb/MIKADO/Publikasjoner/
4 http://www.klimatre.no/index.php?page=publikasjoner

1.3 Objectives

The objective of the first part of this project work (carried out in the fall semester 2010) was to establish an overview, suited for use in environmental assessments, of the flows of wood based products throughout the Norwegian wood products sector. The purpose of establishing this wood flow mapping was to provide important information needed in solving allocation issues in environmental assessments, and in performing scenario analyses where these flows are rearranged.

In the second part of the project work (carried out in the spring semester 2011), the main objective was to illustrate how such an overview can be utilized within the LCA/IOA framework to perform scenario assessments which are highly representative to the studied system (in this case the Norwegian wood products sector). The developed model should be able to assess 'the big picture', but also zoom in on specific industries and products. Embedded in this objective, also lied an intention of providing information on how the total impacts, and the breakdown of these onto various processes, change when the flows are rearranged (e.g. to increase the share of bioenergy). However, the main purpose was to illustrate the possibilities available within the developed model, not to make final conclusions on how we should best utilize our wood resources.

The objectives of the entire project can be formulated as a series of questions:

Q1: What goes where of wood resources and wood based products in the Norwegian economy?

Q2: How can such an overview be utilized in environmental system analysis?

Q3: What changes to the process datasets in the standard LCA background databases (e.g. Ecoinvent) are required to make an environmental assessment of Norwegian wood products representative to Norwegian conditions?

Q4: How can a hybrid-LCA model help us assess the environmental consequences (on both national-, sector- and product level) of increasing the share of bioenergy, assuming a fixed wood resource base?

1.4 Content outline

In section 2, the underlying LCA- and IOA methodology is presented, including the basic mathematics of these frameworks. Section 3 describes the process of building the assessment model for the Norwegian wood products sector, including data collection and life cycle inventory (LCI) building. Then, in section 4, the LCA results, on both national-, sector- and product level, are presented and explained. The results and their implications, the most important assumptions made, as well as potential contributions from this thesis are discussed in section 5.

2 METHODOLOGY

In this section, the methodology behind the developed assessment model is introduced. First, some general characteristics of LCA, IOA and hybrid-LCA are presented, followed by the basic mathematical framework within these methods. Finally, the applied life cycle impact assessment method (ReCiPe) is introduced and a short discussion is carried out regarding how biogenic carbon emissions within the system are dealt with.

2.1 Environmental assessment methods

The increasingly attention shown to environmental aspects from both governments, industries and the public, has further triggered the need for credible, scientific methodologies in environmental system analysis. Methodologies ensuring fair comparisons, when analyzing products, organizations or technologies' environmental impacts, are necessary in order to have best possible grounds for decision-making. Life Cycle Assesment (LCA) and Input-Output Analysis (IOA) are the most important methodological frameworks in this context.

Traditional, process-based LCA has for several years been the dominant tool in environmental system analyses. The mentality in this approach is that one consider the inputs going into (and emissions occurring within) a given process. However, these inputs will in turn require their own inputs, etc, etc. In order to stop this infinite process line, the LCA practitioner will have to establish some system boundaries. Depending on the where these boundaries are defined, as well as the characteristics of the studied system, process-based LCA can therefore sometimes suffer in lack of completeness. On the other hand, the processes within the system boundaries are normally modeled with a high level of detail.

In recent years the concept of 'hybrid life cycle assessment' has become the preferred choice for many LCA practitioners as it involves more complete system boundaries than the traditional approach. The name hybrid-LCA refers to how this approach combines LCA- and IOA methodology in order to 'extract' the respective strengths of these two frameworks, while cancelling out their weaknesses.

2.1.1 Life Cycle Assessment

LCA is a standardized tool (ISO 14040 series) that covers both all environmental impact categories as well as all life cycle stages of a product, technology or activity (Baumann and Tillman, 2004). Although the name originated from the focus on including all life cycle phases, it is today well acknowledged that focus on processes further upstream might be just as important (Strømman, 2008, p.3). In other words, making sure that the system boundaries includes important upstream processes, and accurate modeling of these, can be equally significant to the overall environmental impacts as the processes within the life cycle. One major advantage of the holistic perspective which LCA represents is its ability to efficiently deal with 'problem shifting' (i.e. generating one problem while solving another) which is likely to occur if e.g. some impact categories or life cycle stages are neglected.

When modeling within the LCA framework one generally distinguishes between the foreground system and the background system. By foreground system we mean the life cycle activities for which specific data is collected in the given study, while the background system includes the activities described in standard LCA databases (e.g. Ecoinvent). These databases contain life cycle inventories on several thousand processes and products, and are integrated in commercial LCA software such as e.g. SimaPro and GaBi.

According to the ISO standards, a LCA consist of the four phases as shown in figure 1. In the first phase, the scope (including system boundaries) is defined according to the goal(s) of the study. Phase two consists of inventory building, i.e. collection and modeling of process data such as e.g. material input, energy input, emission data and allocation factors between multiple outputs. This phase is generally the most time consuming phase in life cycle assessments. The third phase is environmental impact assessment and is carried out by applying one of the many different impact assessment methods, which also are implemented in the commercial LCA software. These methods vary somehow in which impact categoriy indicators they use, and in some of the basic assumptions made such as e.g. time horizon for impacts. Consequently, the LCA practitioner must choose an impact assessment method in context of the defined goal and scope of the study. The impact assessment phase includes calculation of total emissions and corresponding environmental impact potentials, normally carried out by commercial LCA software. LCA is an iterative technique, and the practitioner must continuously reconsider assumptions made, as new information may emerge along the way. In some cases, there may even be a need to adjust the goal and/or the scope. The fourth phase, called interpretation, is a continuous process carried out in parallel to all the other phases so that potential errors and contradictions ca be found and corrected. Finally, when an impact assessment has been completed, a sensitivity analysis of the most uncertain data and/or assumptions is normally performed.

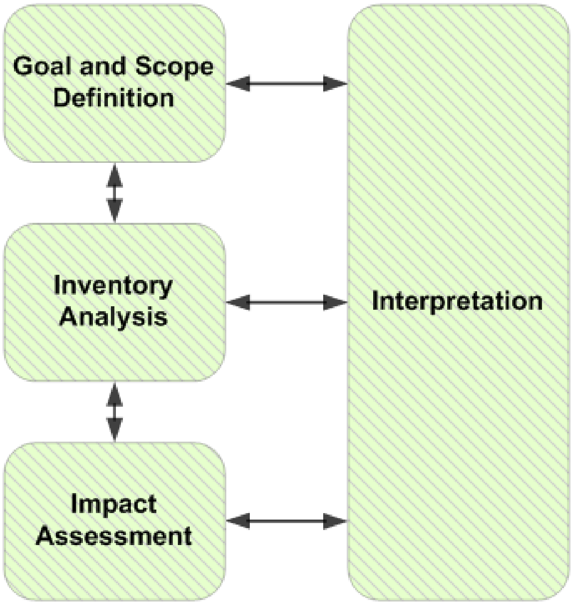

Figure 1: The four phases of LCA

2.1.2 Input-Output Analysis

The concept of Input-Output Analysis (IOA) was developed by the Nobel Laureate in Economics, Wassily Leontief, in the 1930s. The idea of IOA is to accurately describe technology interrelationships in order to analyze repercussions of our production and consumption activities. Traditionally, this framework was mainly used in macroeconomic analyses, but in the recent years it has become ever more common to apply this methodology in environmental system analyses as well (Strømman, 2008, p.88).

The first step in IOA is establishing the Make & Use tables for the industries/sectors of interest. These are simply tables describing what a given industry produced and consumed of different products within a given time period, and the data can be given either in physical or monetary units. When used together with known emission data for the different industries, the tables can be used to allocate the overall emissions onto the different products and/or industries. Quite often, the necessary data for compilation of the Make & Use tables has been developed by statistical offices such as e.g. Statistics Norway (SSB). However, this is typically data with a high aggregation level, especially for small economies such as the Norwegian economy (Strømman, 2008, p.91), and when Make & Use tables for a specific sectors is required one is often forced to search for alternative sources (ref. motivation for this project work).

In contrast to process-based LCA, the IOA framework provides excellent completeness as it contains all the necessary feedback loops. Unfortunately, the level of detail is considerably lower than in process-based LCA due to the aggregation of industries and technologies.

2.1.3 Hybrid-LCA

As previously explained, the idea of hybrid life cycle assessments is to combine the respective strengths of LCA and IOA in order to achieve a best possible framework for environmental system analysis. Within hybrid-LCA we further distinguish between different approaches. The three most common approaches to hybrid-LCA are called: tiered-, IO based- and integrated hybrid-LCA. In tiered hybrid-LCA, an additional background system based on IO data is introduced in order to cover what is missed out by the original background system. This approach is easy to use and allows for relatively easy upgrades of already performed LCAs. Its challenge is to avoid double counting, i.e. the same background processes are present in both the original- and the introduced IO background system. This issue can be solved by some manipulations of the applied matrices, but this will require some effort from the LCA practitioner.

The IO-based approach, on the other hand, simply replaces the original background LCA database with the IO background system. This implies that the foreground system must be well developed in order to outweigh the issue of aggregation errors in the IO dataset. The IO based approach also assumes that the product flows in the studied foreground system are so small that they are negligible compared to the flows on a national level (i.e. the IO background systems inputs from the studied foreground system are minimal).

The most advanced approach of the three, integrated hybrid-LCA, is quite similar to the IO based approach, but can also be used for modeling of foreground systems with bigger magnitude (i.e. not negligible). Again, the background IO dataset has to be modified, making this the most complicated method of the three. Generally, it can be concluded that the question of which approach is the best depends upon accessibility of data and the system studied (Strømman, 2008, p.98).

In this project work however, a fourth approach has been applied. As one of the main objectives is to assess the environmental implications of different wood flow scenarios within the Norwegian sector, it was necessary to obtain the interrelationships between the domestic wood consuming industries. Therefore, it is in this case the wood related interactions within the foreground system (A_{ff} - matrix) who are modeled based on input-output methodology, while the backgrounds system (A_{bb} - matrix), as well as the foreground system's 'non-wood inputs' (A_{bf} - matrix) and direct emissions (F_f - matrix), are modeled according to traditional process-based LCA procedures. These matrices will be further explained in the following section.

2.2 Basic mathematics in environmental system analysis

The mathematical formulation of IOA is quite similar to what we find in LCA, making it easy to combine the two methods in a hybrid-LCA. In this section, the most basic mathematics of LCA and IOA will be presented. First, the necessary calculations needed to convert the Make & Use tables into more useful matrices will be introduced. This will hopefully make it possible for readers unfamiliar to this framework to follow the calculations in the Matlab-file (Appendix A), and interpret the various matrices presented throughout this report.

The UN guidelines described in "*Handbook of Input-Output Table Compilation and Analysis*" (United Nations, 1999) is used as basis for the IOA framework, while "*Methodological Essentials of Life Cycle Assessment*" by Anders H. Strømman (2008) is used as basis for the LCA framework.

2.2.1 Nomenclature in LCA

pro	= # of processes
pro_f	= # of foreground processes (i.e. processes defined in study)
pro_b	= # of background processes (i.e. processes from generic databases)
str	= # of stressors
imp	= # of impact categories
A	= Requirements matrix (pro·pro)
A_{ff}	= Foreground processes requirements matrix ($pro_f \cdot pro_f$)
A_{bb}	= Background processes requirements matrix ($pro_b \cdot pro_b$)
A_{bf}	= Inputs of background processes to foreground system ($pro_b \cdot pro_f$)
x	= Output vector (pro·1)
x_f	= Foreground processes output vector ($pro_f \cdot 1$)
X_{bf}	= Output from background system caused by foreground system ($pro_b \cdot pro_f$)
y	= Demand vector (pro·1)
M_{bf}	= Demand placed upon background system by foreground system ($pro_b \cdot pro_f$)
L	= Leontief Inverse matrix (pro·pro)
F	= Stressor intensity matrix (str·pro)
F_f	= Foreground processes stressor intensity matrix ($str \cdot pro_f$)
F_b	= Background processes stressor intensity matrix ($str \cdot pro_b$)
e	= Total emissions vector (str·1)
C	= Characterization matrix (imp·str)
d	= Total impacts vector (imp·1)
D_{pro}	= Impacts caused by each process (imp·pro)
$D_{pro,f}$	= Impacts caused by each foreground process ($imp \cdot pro_f$)

2.2.2 Mathematical operations in LCA

The requirements matrix (A) shows the amount of input needed from other processes to produce one output of a given process [5]. It can be thought of as a 'cooking recipe', where each column represents the ingredients for that specific process.

$$A = \begin{bmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{13} \\ \vdots & \ddots & \vdots \\ a_{31} & \cdots & a_{33} \end{bmatrix} \tag{1}$$

, where

$$a_{ij} = \frac{\text{amount of i required}}{\text{output of j}} \tag{2}$$

In order to calculate the total emissions, and corresponding environmental impact potentials, from a system, we need to find the output vector (x). The output vector shows the total output of each process in the system as a result of the demand (both internal and external) faced by the system. This can be illustrated by considering a simple system of three processes as shown in equation (1). The total output of e.g. process 1 is then found as shown in equation (3).

$$x_1 = \overbrace{a_{11} \times x_1 + a_{12} \times x_2 + a_{13} \times x_3}^{\text{int. dem.}} \overbrace{+ y_1}^{\text{ext. dem.}} \tag{3}$$

Equation (3) can then be generalized as:

$$x = Ax + y \Leftrightarrow (I - A)x = y \Leftrightarrow x = ((I - A)\text{^-1})\,\mathrm{y} \tag{4}$$

, where

$$\mathrm{L} = ((I - A)\text{^-1}) \Rightarrow \mathrm{x} = \mathrm{Ly} \tag{5}$$

[5] A process in this context could imply either a product, a service, an industry or in fact a production process

L is called the Leontief Inverse [6], and its columns can be interpreted as the cooking recipes per unit external demand placed on that process, i.e. unlike the requirements matrix it also includes the indirect requirements for other foreground processes.

The output vector (x) can then be used together with a stressor intensity matrix (F) to calculate the overall emissions (e) resulting from a given demand.

$$F = \begin{bmatrix} F_f & F_b \end{bmatrix} \tag{6}$$

$$e = Fx \tag{7}$$

The characterization matrix (C) is used to convert an endless list of emissions into a set of useful environmental impact categories such as e.g. Global Warming Potential (GWP), Acidification Potential (AP), Human Toxicity Potential (HTP), etc. The characterization factors allow us to convert emissions of different substances, with contributions to the same environmental problem, into equivalents. The total impacts vector (d) can then be found as shown in equation (8).

$$d = Ce \tag{8}$$

In most environmental assessments it is of interest to know how the total impacts of a system are distributed between the different processes. This is done by placing the elements of the output vector (x) on the diagonal in a matrix with zeroes elsewhere ($\hat{x}$), and then multiply by C and F.

$$D_{pro} = CF\hat{x} \tag{9}$$

However, it is generally of even greater value to know how the total impacts are distributed on just the studied foreground processes, i.e. allocating the impacts of the background system onto the foreground processes based on their respective responsibilities for these impacts. Establishing the matrix showing this ($D_{pro,f}$) requires some effort, as shown in equation (10) - (13). First, we find the output vector for processes in the foreground system (x_f).

[6] Named after Wassily Leontief who developed this mathematical framework in the 1930's.

$$x_f = (I-A_{ff})^{-1} y_f \quad (10)$$

Then, it is possible to find the demand that is placed upon the various background processes by each of the foreground processes (M_{bf}), and the resulting output matrix (X_{bf}).

$$M_{bf} = A_{bf}\,\hat{x}_f \quad (11)$$

$$X_{bf} = (I-A_{bb})^{-1} M_{bf} \quad (12)$$

Finally, we can calculate the distribution of impacts onto the various foreground processes.

$$D_{pro,f} = CF_f\,\hat{x}_f + CF_b X_{bf} \quad (13)$$

Contribution analysis in LCA includes many more possibilities to investigate specific processes or stressors even further, but the framework presented above represent the essence of the calculations carried out in this project work.

2.2.3 Nomenclature in IOA

m	= # of product categories
n	= # of industry categories
M	= Make matrix ($m \cdot n$)
U	= Use matrix ($m \cdot n$)
Y	= Vector of net final demand for products ($m \cdot 1$)
Y_{ind}	= Vector of net final demand for industries ($n \cdot 1$)
q	= Output vector products ($m \cdot 1$)
g	= Output vector industries ($n \cdot 1$)
A_{mm}	= Requirements matrix products ($m \cdot m$)
A_{nn}	= Requirements matrix industries ($n \cdot n$)
x_m	= Output vector products ($m \cdot 1$)
x_n	= Output vector industries ($n \cdot 1$)
L_{mm}	= Leontief Inverse matrix products ($m \cdot m$)
L_{nn}	= Leontief Inverse matrix industries ($n \cdot n$)

B = Use coefficient matrix (m· n)

G = Market share matrix (n· m) [7]

H = Product mix matrix (m· n) [8]

In order to avoid confusion, it should be noted that the q and g vectors are derived directly from the collected data in the Make and Use tables, while x_m and x_n are end products of the mathematical operations. The latter are used to check that the requirements matrices are balanced and complete, by comparing the different vectors. If x_m equals q and x_n equals g, then the material (primal) balance is fulfilled, i.e. the requirement matrices are correct.

2.2.4 Deriving the IOA matrices

In section 2.2.2 some of the basic mathematics of LCA was described. Now we shall see how this framework can be applied to convert the Make & Use tables into more useful requirement matrices (A_{mm} and A_{nn}) that can be applied in environmental system analysis applications. As previously mentioned, a hybrid approach where the foreground system is modeled based on input-output data was applied in this study. This means that the A_{mm} matrix (i.e. requirements matrix for products) derived from the Make & Use tables was used as basis for the A_{ff}.

There are two main IOA constructs, i.e. two methods for deriving the requirement matrices. These two are called ‘the industry technology assumption’ (IT) and ‘the commodity technology assumption’ (CT) (United Nations, 1999, p. 86-98). Due to the situation that one industry often produces several products, and one type of product often is produced by several industries, assumptions need to be made regarding to ‘ownership of technology’. As the name implies, IT assumes that each industry has one given technology (i.e. technology belongs to industry), while CT assumes that each product has one given technology (i.e. technology belongs to product). The CT assumption requires an equal number of product- and industry categories, which means that the IT assumption was best suited in this study. The derivations in the IT construct are presented below.

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[7] Normally, D is used to denote the market share matrix, but in order to avoid confusion with the impact matrices (d, D_{pro} and $D_{pro,f}$) G is applied here.

[8] Normally, C is used to denote the product mix matrix, but in order to avoid confusion with the charcterization matrix (C) H is applied here.

The Net Final Demand vectors for products (Y) and for industries (Y_{ind}), the output vectors (q and g), the Use Coefficient matrix (B), the Market Share matrix (G) and the Product Mix matrix (H) are calculated as shown below.

$$Y = \text{final domestic demand} - \text{import} + \text{export} \quad (14)$$

$$Y_{ind} = GY \quad (15)$$

$$q = Ui + Y \quad \text{, where i is a vector of 1's } (n \cdot 1) \quad (16)$$

$$g = M^T j \quad \text{, where j is a vector of 1's } (m \cdot 1) \quad (17)$$

$$B = U \operatorname{diag}(g)\ \wedge^{-1} \quad (18)$$

$$G = M^T \operatorname{diag}(q)\ \wedge^{-1} \quad (19)$$

$$H = M \operatorname{diag}(g)\ \wedge^{-1} \quad (20)$$

First, we derive the product-by-product requirements matrix, A_{mm}:

From (18): $\Rightarrow Ui = Bg$ (21)

From (16) + (21): $\Rightarrow q = Bg + Y$ (22)

From (19): $\Rightarrow M^T = G \operatorname{diag}(q)$ (23)

From (17) + (23): $\Rightarrow g = Gq$ (24)

From (22) + (24): $\Rightarrow q = BGq + Y \Leftrightarrow (I-BG)q = Y$ (25)

From (4) and (25): $\Rightarrow (I-A)x = Y \Rightarrow \underline{A_{mm} = BG}$ (26)

Then, we derive the industry-by-industry requirements matrix, A_{nn}:

From (22): $\Rightarrow Gq = GBg + GY$ (27)

From (23)+(24)+(27): $\Rightarrow g = GBg + Y_{ind} \Leftrightarrow (I-GB)g = Y_{ind}$ (28)

From (4) + (28): $\Rightarrow (I-A)x = Y \Rightarrow \underline{A_{nn} = GB}$ (29)

The final output vectors are derived from the following equations:

$$x_m = L_{IT,mm} Y \tag{30}$$

$$x_n = L_{IT,nn} Y_{ind} \tag{31}$$

2.3 Life Cycle Impact Assessment (LCIA) method - ReCiPe

The ReCiPe life cycle impact assessment method was developed in order to harmonize the CML (midpoint oriented) and Eco-indicator (endpoint oriented) methods (Goedkoop et al., 2009).[9] Life cylce impact assessment requires several conversion and aggregation steps in order to convert emissions into midpoint indicators, and midpoint indicators into endpoint indicators. For some of these steps, uncertainties have been incorporated into the ReCiPe framework in form of different perspectives. These are called: the individualist (I), the hierarchist (H) and the egalitarian (E). The individualist (I) is a technology optimist and environmental sceptic who uses a short time frame as he believes that generated environmental problems can be solved with future technology. The egalitarian (E), on the other hand, is extreme risk averse and concerned with sustainability. This perspective uses therefore a long time frame. The hierarchist (H) perspective follows most common policy principles and can be considered to be a 'middle way'. For this reason, the ReCiPe (H) impact category indicators, at midpoint level, were applied in this assessment.

2.4 Climate change contribution from biogenic carbon

When neglecting indirect emissions (e.g. due to transport), bioenergy has so far been considered to be climate neutral. The idea has been that as long as the biomass being extracted from nature is replanted at a corresponding rate the amount of carbon in the atmosphere will remain constant over time, as the biomass will absorb an equal amount of carbon during growth as it releases during combustion and decay.

This phenomenon is generally referred to as 'carbon neutrality'. However, recent research has demonstrated that carbon neutrality (as is the case of biomass) and climate neutrality are two separate issues. When for instance a tree is chopped down and burned to produce heat, the

[9] Midpoint oriented methods use impact category indicators at the midpoint level such as e.g. acidification and climate change, while endpoint oriented methods apply indicators at the endpoint level such as e.g. damage to ecosystem quality and damage to human health.

carbon it contains is released to the atmosphere within a short period of time. Even if a new tree is replanted immediately, it will take several decades before the same amount of carbon has been absorbed. Consequently, the carbon released in form of CO_2 and CH_4 will spend a considerable amount of time in the atmosphere before being absorbed. During this time it will contribute to global warming and should therefore not be considered climate neutral.

Within the Department of Energy and Process Engineering at The Norwegian University of Science and Technology (NTNU) a group of scientists have recently developed a method to estimate the climate impact of biogenic carbon dioxide emissions. With this model they have calculated different global warming potential (GWP) characterization factors for biogenic CO_2 based on different assumptions regarding natural carbon sinks, biomass rotation periods and impact time horizons. The factor chosen in this assessment is calculated according to the 'full impulse response function' (FIRF) method where it is assumed that CO_2 in the atmosphere can be removed both by the ocean and the terrestrial biosphere. With an assumed time horizon and rotation period of both 100 years, the resulting factor is given as 0.43 kg CO_2-eq. per kg biogenic CO_2 (Cherubini et al., 2011, p.10). For biogenic methane, the IPCC standard factor of 25 kg CO_2-eq. per kg CH_4 was applied.

3 MODEL

This section describes the work carried out in developing the assessment model. First, a general description of the studied system (including system boundaries) is presented, followed by a review of the data collection process in the wood flow mapping. The resulting Make & Use tables for wood, and subsequent A_{ff} matrix, in the studied year (2006) are then shown, before an alternative wood flow scenario (and its respective A_{ff} matrix) is presented. Finally, assumptions and modifications in the remaining parts of the model (i.e. A_{bf}, F_f and Y) are described.

3.1 System description

The wood based sector in Norway is in this work defined to consist of the following industries: forestry, sawmills and woodworking factories, pulp production, paper production, wooden board production, pellets- and briquettes production, bioethanol production, recovery of wood- and paper waste and heat production. Heat production based on biofuels is further divided into: waterborne heat (i.e. district heating) from burning wood, heat from firewood (i.e. logs) and point source heat from pellets- and briquettes.

In addition to the wood related industries, the production of gypsum boards, gasoline, heat from oil and waterborne heat from 'non-wood fuels' are included in the analysis in order to be able to calculate the overall environmental effect of changing the production levels of the different wood products, while maintaining the same demand level. This small selection of non-wood product categories was chosen as they represent the most likely alternatives to be substituted in an alternative scenario where more wood is used for bioenergy purposes.

For the case of transportation fuels, only road transportation was considered. In principle, wood can be used to produce either bioethanol, biodiesel (Fischer-Tropsch process) or biogas. However, for simplicity only bioethanol is considered in this assessment. Bioethanol can be used to phase out gasoline and these two fuels are therefore the only ones considered in this analysis, i.e. other fuels are irrelevant as they would not be replaced in an alternative scenario.

Plywood and veneer- and laminated boards are also excluded from the analysis, as the collected data indicated insignificant domestic production of these products.

Final domestic demand, imports and exports was defined as separate sectors. Final domestic demand includes all other domestic consumers (i.e. excluding the defined industries), which basically means households and other domestic industries. Some of the industries within the wood value chains, such as e.g. furniture making and construction, are not a part of the defined system as the wood being used for such purposes is of the highest quality and price, and therefore highly unlikely to be used for bioenergy purposes. Consumption of wood products in these industries is however included in the final domestic demand.

Wood raw materials are delivered from domestic forestry plus imports, and the system's outputs are delivered to exports and final domestic demand. Additionally, wood based products are traded within the system (i.e. the defined domestic wood- and forestry industry). The figure below shows a simplified overview of the studied system, where the light green boxes refer to the domestic industries within the wood products sector, while the light yellow boxes refer to domestic industries outside this sector.

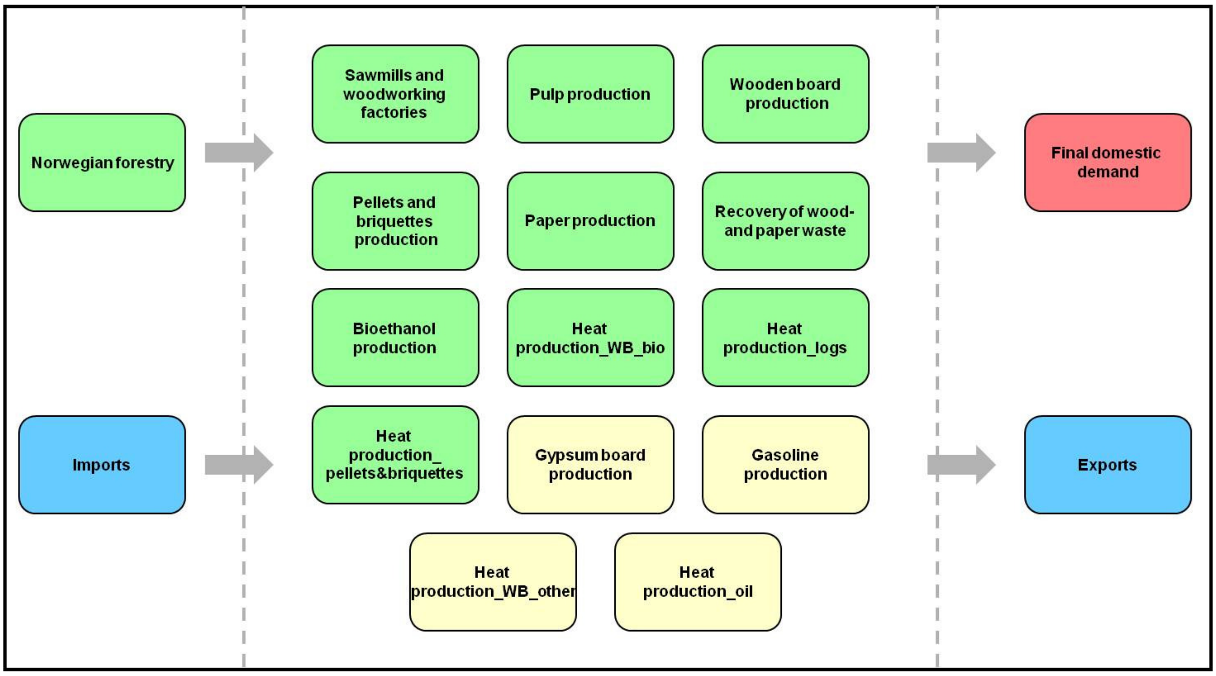

Figure 2: Simplified system overview

3.2 Accounting wood flows in Norway

This part of the analysis was mainly carried out during my project work in the fall semester of 2010, and some additional information about this process can be found in my project report (Grinde 2010). Since then, some additions and adjustments have been made to the Make & Use tables and these are, in addition to the original data, described in this section. The objective of this wood flow mapping was to provide an 'as-accurate-as-reasonable' representation of the wood based product flows in Norway, suited for use in environmental assessments. It quickly became clear that establishing such an overview would require more effort than initially expected. Even though much data exist on overall annual felling quantities and on final production of end products, there is a considerable lack of data on intermediate flows within the wood related industries. Other factors that provided challenges in this process where: a lot of aggregated data (i.e. low level of detail), variations in nomenclature and/or definition of product categories, variations in use of units requiring e.g. average density numbers for conversion, and finally, contradictions between different data sources. However, this wood flow mapping being an apparently, relatively unexplored field in Norway also provided an extra motivation, and justification, for establishing such an overview.

In order to solve some of the above mentioned issues in collecting data, some rough estimations and assumptions were necessary. Data collection in environmental system analysis is, as in other areas, a trade-off between the extra required effort and the expected significance of having slightly more accurate data. As any other assessment, environmental system analysis is not an exact science. The high numbers of parameters, both in the life cycle inventories and the impact assessment methods, and their respective uncertainties, imply that the final results will never be 100% representative to the real world. Still, as long as all 'simplifications' are well founded, they can still provide highly valuable information to decision makers.

Another essential aspect of this work has been bringing all the data together and balancing the flows in order to make total consumption (Use) and total production (Make) cancel out, i.e. a steady state system. This is necessary in order to be able to apply the input-output framework, but did require making some quite simple assumptions. For instance, in cases where data on one producer of consumer category was missing (e.g. total domestic production, total domestic consumption and exports were known but imports was unknown) this category was used to balance the total consumption with total production.

All collected data for the wood flows are from 2006. The only exceptions are the data on wood- and paper waste which is from 2005, and some allocations which are based on situations in other recent years (2000-). These are further described in the following section. Although it would have been desirable to have more recent data, this would imply collecting much of the data first hand which would be too time consuming to justify. Especially since the statistics from Statistics Norway indicate that the 'big picture' in the Norwegian wood industries has remained rather constant for the last decade. Of course, there are some exceptions to this statement such as e.g. the increased harvesting of forest residues and subsequent use of wood chips in water borne heating systems. Adjusting for such exceptions would however cause the requirements matrices to change, giving an incorrect impression of the allocation between different product inputs and outputs in a given industry at a given time. Hence, such adjustments were avoided and all data are from the same year ensuring consistency and transparency.

The two main sources of data for the wood flow mapping were the master thesis "*Logs, wood based products and pulp & paper products in Norway - product flows and value added in the wood based value chain*" from 2009 (data from 2006) by Kjetil André Rødland, as well as official statistics from Statistics Norway including external trade-, forestry- and agricultural statistics. Although these sources constitute the basis of the collected data, a critical perspective was maintained throughout the study and changes were made wherever data contradicted with other, more credible sources [10] or a higher level of detail was required. For these changes other written sources such as e.g. official reports and scientific journals were utilized. Furthermore, personal communication with key persons within the following organizations provided an important source of data: Statistics Norway (Trond Amund Steinset and Marius Berg), The Norwegian Bioenergy Association (Arnold Kyrre Martinsen), Norwegian University of Life Sciences (Torjus Folsland Bolkesjø and Erik Trømborg), Treteknisk Institutt (Per Otto Flæte and Lars Gunnar Tellnes) and The Norwegian Forest and Landscape Institute (Simen Gjølsjø).

[10] As Rødland's master thesis is a secondary source of data, other first hand sources were chosen if they were considered to be more credible

Below, complementary information is given for the respective industries and products. Specific sources for different data are named, and necessary assumptions and simplifications are described. If no specific source is listed, Rødland's master thesis can be assumed to be the source for data on that flow. Although all the numbers should be approximately correct, it was in several instances necessary to perform small modifiactions in order to make the flows balance. It would not be practical to list and explain all of these minor changes, nor is it important as the complex nature of the studied flows implies that the real world situation probably is slightly different from the applied sources anyway. The final wood flow overview is given in the Make & Use tables in section 3.3.

3.2.1 Norwegian forestry

In this industry much data is available and well documented. Felling of saw timber and pulpwood is found in the annual published forest statistics report by Statistics Norway. Statistics Norway receives these numbers from the "*Wood trade database*" which is run by Skog-Data AS on behalf of Norwegian Agricultural Authority. This data is the same as the one utilized by Rødland (2009). Flows in and out of storage (i.e. changes in wood stocks) are not treated as part of a separate sector in this work. This is because the IOA framework requires the flows to be balanced, i.e. total input equals total output. According to Rødland, 590 000 sm^3 saw timber was taken from storage and 850 000 sm^3 pulp wood was sent to storage, in 2006. In this work, these flows are instead included in forestry production and net final demand, respectively.

Cutting of firewood was also found in Rødland's master thesis, while chip production from energy wood [11] and forestry residues (mainly branches and tops) was estimated by assuming no export of this commodity[12] and then applying Statistics Norway's district heating statistic which states the consumption of wood chips in district heating plants. In 2006 this number was 132 000 tonnes. In solid cubic metres that corresponds to approximately 297 000, when applying a general wood density of 0.44 tonnes/sm^3. The proportion allocation between energy wood and forestry residues was made based on figure 3 in "*IEA Bioenergy task 40 - Country Report 2009 for Norway*" (Trømborg and Leistad, 2009, p.11). This report indicated a slightly higher proportion of energy wood compared to forestry residues. Import data for

[11] Round wood of low quality, i.e. not suited for wood working or wood processing purposes
[12] Transport is normally a significant cost factor in the chip value chain, creating incentives for local use

these two were obtained through personal communication with Marius Bergh at Statistics Norway.

Data for use of pulpwood was found in the "*Joint Wood Energy Enquire 2007*" table, developed by Statistics Norway. It was assumed that the situation in 2006 was similar to the one in 2007.

3.2.2 Sawmills and woodworking factories

All of the data on domestic production in this sector was found in Rødland's master thesis., except the estimation on bark production which as obtained through personla communication with Lars Gunnar Tellnes at Treteknisk Institutt. Data for imports and exports was found in table 3.6.2 in Statistics Norway's agricultural statistics publication of 2007 (Rognstad and Steinseth, 2008, p. 159), with data for 2002-2007 available. Data collected through personal communication with Marius Bergh was used to subtract the amount of wood waste in the foreign trade table in the agricultural statistics, where sawdust and wood waste were put together in one aggregated category.

The allocation of use of industrial residues was made based on data found in the "*Bioenergy in Norway – potentials, markets and policy instruments*" report (Langerud et al., 2007, p.40-41).

3.2.3 Pulp production

Rødland operates with an aggregate pulp category. Due to significant differences in pulp production technology, it was desirable with a higher aggregation level in this assessment. Production, imports and exports of different types of pulps was found in the Norwegian wood processing industry's key figures for 2006 (Foss, 2010).

3.2.4 Paper production

All data taken from Rødland's master thesis (2009).

3.2.5 Wooden board production

All data here were taken from Rødland's master thesis (2009) with an exception for import data on fibre- and particle boards. According to Rødland, there is no import of these products in Norway and he specifically states that Norway is a net exporter in this area. This is however not true for fibre boards according to table 3.6.2 in Statistics Norway's yearly agricultural statistics publication, which operates with import of 192 000 sm^3. The publication also states that Norway imported 101 000 sm^3 of particle boards in 2006. The data from Statistics Norway was utilized in this work, as the author considered this to be the most credible source. Average densities of 0.55 tonnes/sm^3 (fibre boards) and 0.63 tonnes/sm^3 (particle boards) were applied to convert the data provided by Statistics Norway from tonnes to sm^3.

3.2.6 Gypsum board production

There are two major Norwegain gypsum producers, Gyproc and Norgips. Through personal communication with the sales manager (Vidar Eikeset) at Gyproc, estimations on total domestic production, imports and exports were made.

3.2.7 Pellets- and briquettes production

The Norwegian Bioenergy Association (NoBio) annually publishes a report called "*Bioenergy in Norway – Market report*". In the 2009 edition (The Norwegian Bioenergy Association, 2010) , domestic production, import and export of pellets and briquettes in 2006 was found. Less easily available was the input structure of wood material into this production. For this, estimations were made based on interviews with 15 Norwegian producers of pellets and briquettes. Their input structures was used as a norm and extrapolated to match total production figures.

3.2.8 Recovery of wood- and paper waste

All data taken from Rødland's master thesis (2009).

3.2.9 Bioethanol production

Borregaard is a major Norwegian pulp producer, and the only major producer of bioethanol (as well as biomethanol and various chemical products) derived from wood. Kjersti Garseg at Borregaard provided the data for Norwegian production of bioethanol. The input structure found in the supplementary material to the article '*Life cycle assessment of second generation bio-ethanols produced from Scandinavian boreal forest resources: A regional analysis for Middle Norway'* (Bright et al., 2009b), was used to determine an approximate for the bioethanol production's wood requirements.

3.2.10 Gasoline production

Data on annual domestic demand for gasoline was taken from Statistics Norway's energy balance for 2006 (Statistics Norway, 2011c). Since this analysis is of a 'comparative' nature, the production of gasoline for export was not considered as only a small fraction of the domestic consumption would be substituted by bioethanol in the alternative scenario.

3.2.11 Waterborne heat based on biomass

Total water borne heat production from wood fuels was found in Statistics Norway's district heating statistics (Statistics Norway, 2011a and 2011b) to be approximately 430 000 MWh. As for pellets- and briquettes production, the challenge was to get good estimates on how much of different input materials were used in this production.

According to Arnold Kyrre Martinsen at The Norwegian Bioenergy Association, the sales figures for pellets and briquettes sold in bulk, can be assumed to be used in water borne heating systems. For pellets this fragment constitute 48% of total sales and the domestic allocation between water borne heating and other applications, was therefore split 48% to 52%. For briquettes, the equivalent allocation was 86% to 14%.

Rødland states, in his report, that the wood waste used in energy recovery was approximately 800 000 sm^3 in 2006 (Rødland, 2009, p.36). However, he does not distinguish between whether or not the energy recovery takes place domestically or in other countries. After having converted the number into tonnes (by applying the same general wood density as before, i.e. 0.44 tonnes/sm^3) an allocation between domestic use (i.e. water borne heating) and export was set to 20% and 80% respectively. This allocation was merely made based on a subjective impression of the current market in Norway, as most of the wood waste is exported to Sweden for incineration (Nordland et al., 2003, p.19).

3.2.12 Waterborne heat based on other sources

Total water borne heat production from non-wood fuels was also found in Statistics Norway district heating statistics (Statistics Norway, 2011a and 2011b). Waste heat and electricity were neglected as energy sources in district heat production in this assessment as they were considered to be unlikely to be substituted by biomass in an alternative scenario.

3.2.13 Heat from burning of wood logs

The amount of heat from burning of wood logs in stoves and fireplaces was estimated based on the annual consumption of fire logs, an average conversion factor of 0.78 sm^3/MWh and a combustion efficiency of 60% (Bolkesjø, 2004, paper V p.7).

3.2.14 Heat from burning of pellets & briquettes

Similar to the heat category above, the amount of heat from burning of pellets and briquettes in stoves was estimated based on the annual consumption of these products, an average density of 0.65 tonnes/sm^3, an average conversion factor of 0.64 sm^3/MWh and a combustion efficiency of 80% (Bolkesjø, 2004, paper V p.7).

3.2.15 Heat from burning of oil

The 2006 consumption of oil in heat production was estimated by adding the columns in figur 15.1 found in the report *'Klimakur 2020'* (The Norwegian Climate and Pollution Agency, 2010, p.156).

3.3 Make & Use tables - Norwegian wood products 2006

In order to facilitate an orderly presentation of the Make and Use tables, the product- and sector categories are given acronyms as shown in table 1 and 2 below. The tables operate, depending on the product category, with the following four units: solid cubic meters (sm^3), tonnes, gigajoule (GJ) and megawatthours (MWh).

Table 1: Acronyms for product categories

Product cat. #	Acronym	Product name	Unit
1	ST	Saw timber	sm3
2	PW	Pulpwood	sm3
3	EW	Energywood (chips)	sm3
4	BRAT	Branches and tops (chips)	sm3
5	FW	Firewood	sm3
6	SAWNT	Sawn timber (not planed)	sm3
7	PLNDT	Planed timber	sm3
8	CHIP	Cellulose chips,cut-offs,shavings	sm3
9	SAWD	Sawdust	sm3
10	BARK	Bark	sm3
11	FBRD	Fibre boards	sm3
12	PBRD	Particle boards	sm3
13	GYPS	Gypsum boards	tonnes
14	BARK2	Bark	tonnes
15	MPULP	Mechanical pulp	tonnes
16	CTMP	CTMP (chemical thermo-mechanical pulp)	tonnes
17	SCPULP	Semi-chemical pulp	tonnes
18	SULPHA	Sulphatecellulose (chemical pulp)	tonnes
19	SULPHI	Sulphitecellulose incl. dissolving (chemical pulp)	tonnes
20	RECPAP	Post consumer recovered paper and cardboard	tonnes
21	PAPER	Paper and cardboard	tonnes
22	PELBRI	Pellets & briquettes	tonnes
23	RECW	Post consumer recovered wood	tonnes
24	HWBB	Heat_water borne_bio	MWh
25	HWBO	Heat_water borne_other	MWh
26	HLOG	Heat_logs	MWh
27	HPELBRI	Heat_pellets&briquettes	MWh
28	HOIL	Heat_oil	MWh
29	BETHAN	Bioethanol	GJ
30	GASOL	Gasoline	GJ
31	IMPST	Imported saw timber	sm3
32	IMPPW1	Imported pulpwood (softwood from Scandinavia)	sm3
33	IMPPW2	Imported pulpwood (eucalyptus from South Americ	sm3
34	IMPEW	Imported energywood (chips)	sm3
35	IMPBRAT	Imported branches and tops (chips)	sm3
36	IMPFW	Imported firewood	sm3
37	IMPSAWNT	Imported sawn timber (not planed)	sm3
38	IMPPLNDT	Imported planed timber	sm3
39	IMPCHIP	Imported cellulose chips,cut-offs,shavings	sm3
40	IMPFBRD	Imported fibre boards	sm3
41	IMPPBRD	Imported particle boards	sm3
42	IMPGYPS	Imported gypsum boards	tonnes
43	IMPMPULP	Imported mechanical pulp	tonnes
44	IMPCTMP	Imported CTMP	tonnes
45	IMPSCPULP	Imported semi-chemical pulp	tonnes
46	IMPSULPHA	Imported sulphatecellulose	tonnes
47	IMPSULPHI	Imported sulphitecellulose	tonnes
48	IMPRECPAF	Imported post consumer recovered paper and carc	tonnes
49	IMPPAPER	Imported paper and cardboard	tonnes
50	IMPRECW	Imported post consumer recovered wood	tonnes

As the IOA framework requires all outputs of a given industry to have the same unit, it was necessary to establish two categories for bark, BARK (sm^3) and BARK2 (tonnes). BARK represents the bark production at the sawmills who also produce timber (i.e. measured in cubic meters), while BARK2 represents the bark production at the pulp mills who of course produce pulp (i.e. measured in tonnes). If one didn't introduce a second bark category, the g-vector (i.e. industry output) would not be correct for the pulp industry as it would be a sum of figures with different units. In turn, this would lead to a slightly false requirements matrix. The introduction of a second category is further justified by the fact that the entire output of the BARK2- category is produced and consumed within the same industry, i.e. the BARK- and BARK2 flows are never mixed.

Table 2: Acronyms for sector categories

Sector cat. #	Acronym	Sector name
1	NFOR	Norwegian forestry
2	SAWMIL	Sawmills and woodworking factories
3	PULPPR	Pulp production
4	PAPPR	Paper production
5	WBRDPR	Wooden boards production
6	GYPSPR	Gypsum boards production
7	PELBRIPR	Pellets and briquettes production
8	RECOV	Recovery og wood- and paper waste
9	BETHANPR	Bioethanol production
10	GASOLPR	Gasoline production
11	HPRWBB	Heat production_water borne_bio
12	HPRWBO	Heat production_water borne_other
13	HPRLOG	Heat production_logs
14	HPRBIO	Heat production_pellets&briquettes
15	HPROIL	Heat production_oil
16	IMP	Imports
17	FDD	Final domestic demand
18	EXP	Exports

Table 3 and table 4 show the final Make and Use data for the Norwegian wood products setor in 2006.

Table 3: Make table (M) for Norwegian wood products sector (2006)

Product	Unit	NFOR	SAWMIL	PULPPR	PAPPR	WBRDPR	GYPSPR	PELBRIPR	RECOV	BETHANPR	GASOLPR	HPRWBB	HPRWBO	HPRLOG	HPRPEL	HPROIL	IMP	FDD	EXP	Sum
ST	sm3	4590000																		4590000
PW	sm3	4000000																		4000000
EW	sm3	152000																		152000
BRAT	sm3	138000																		138000
FW	sm3	2950000																		2950000
SAWNT	sm3		700000																	700000
PLNDT	sm3		1500000																	1500000
CHIP	sm3		1500000																	1500000
SAWD	sm3		340000																	340000
BARK	sm3		458000																	458000
FBRD	sm3					193000														193000
PBRD	sm3					382000														382000
GYPS	tonnes						140000													140000
BARK2	tonnes			128000																128000
MPULP	tonnes			1437000																1437000
CTMP	tonnes			99000																99000
SCPULP	tonnes			24000																24000
SULPHA	tonnes			586000																586000
SULPHI	tonnes			158000																158000
RECPAP	tonnes								670000											670000
PAPER	tonnes				2109000															2109000
PELBRI	tonnes							93000												93000
RECW	tonnes								934000											934000
HWBB	MWh											430000								430000
HWBO	MWh												1610000							1610000
HLOG	MWh													6500000						6500000
HPELBRI	MWh														30000					30000
HOIL	MWh															6000000				6000000
BETHAN	GJ									480000										480000
GASOL	GJ										64100000									64100000
IMPST	sm3																240000			240000
IMPPW1	sm3																1530000			1530000
IMPPW2	sm3																500000			500000
IMPEW	sm3																5000			5000
IMPBRAT	sm3																4000			4000
IMPFW	sm3																175000			175000
IMPSAWNT	sm3																598000			598000
IMPPLNDT	sm3																364000			364000
IMPCHIP	sm3																781000			781000
IMPFBRD	sm3																192000			192000
IMPPBRD	sm3																101000			101000
IMPGYPS	tonnes																35000			35000
IMPMPULP	tonnes																1000			1000
IMPCTMP	tonnes																			0
IMPSCPULP	tonnes																			0
IMPSULPHA	tonnes																48000			48000
IMPSULPHI	tonnes																24000			24000
IMPRECPAP	tonnes																60000			60000
IMPPAPER	tonnes																608000			608000
IMPRECW	tonnes																15000			15000

Table 4: Use table (U) for Norwegian wood products sector (2006)

Product	Unit	NFOR	SAWMIL	PULPPR	PAPPR	WBRDPR	GYPSPR	PELBRIPR	RECOV	BETHANPR	GASOLPR	HPRWBB	HPRWBO	HPRLOG	HPRPEL	HPROIL	IMP	FDD	EXP	Sum
ST	sm3		4340000																250000	4590000
PW	sm3			1973000		143000				100000								1314000	470000	4000000
EW	sm3							7000				145000								152000
BRAT	sm3											138000								138000
FW	sm3													2945000					5000	2950000
SAWNT	sm3																	278000	422000	700000
PLNDT	sm3																	1458000	42000	1500000
CHIP	sm3		370000	439000		470000		178000		20000									23000	1500000
SAWD	sm3					210000		11000										85000	34000	340000
BARK	sm3		383000															75000		458000
FBRD	sm3																	69000	124000	193000
PBRD	sm3																	172000	210000	382000
GYPS	tonnes																	140000		140000
BARK2	tonnes			128000																128000
MPULP	tonnes				1322000														115000	1437000
CTMP	tonnes				4000														95000	99000
SCPULP	tonnes																		24000	24000
SULPHA	tonnes				309000														277000	586000
SULPHI	tonnes																		158000	158000
RECPAP	tonnes				409000														261000	670000
PAPER	tonnes																	282000	1827000	2109000
PELBRI	tonnes											44000			16000				33000	93000
RECW	tonnes					143000		2000				70000						437000	282000	934000
HWBB	MWh																	430000		430000
HWBO	MWh																	1610000		1610000
HLOG	MWh																	6500000		6500000
HPELBRI	MWh																	30000		30000
HOIL	MWh																	6000000		6000000
BETHAN	GJ																		480000	480000
GASOL	GJ																	64100000		64100000
IMPST	sm3		240000																	240000
IMPPW1	sm3			1530000																1530000
IMPPW2	sm3			500000																500000
IMPEW	sm3											5000								5000
IMPBRAT	sm3											4000								4000
IMPFW	sm3													175000						175000
IMPSAWNT	sm3																	598000		598000
IMPPLNDT	sm3																	364000		364000
IMPCHIP	sm3			781000																781000
IMPFBRD	sm3																	192000		192000
IMPPBRD	sm3																	101000		101000
IMPGYPS	tonnes																	35000		35000
IMPMPULP	tonnes				1000															1000
IMPCTMP	tonnes																			0
IMPSCPULP	tonnes																			0
IMPSULPHA	tonnes				48000															48000
IMPSULPHI	tonnes				18000														6000	24000
IMPRECPAP	tonnes				60000															60000
IMPPAPER	tonnes																	604000	4000	608000
IMPRECW	tonnes					15000														15000

3.3.1 Establishing the A_{ff} matrix

As previously mentioned, it is the A_{mm} matrix which constitutes the A_{ff} matrix in this model. The calculations needed to establish this matrix, explained in the methodology section, were carried out in MATLAB 7.8.0 (R2009a) and are shown as a Matlab-file in Appendix A. Since the Make & Use tables operate with four different units (i.e. sm^3, tonnes GJ and MWh), and all derived matrices result from these tables, the cells in the derived matrices will have different units as well. This can be illustrated with an example. If we for instance. consider the column for 'heat_WB_bio' (HWBB) in the A_{mm}-matrix (table 5) we see that production of water borne, wood-based heating has direct requirements[13] of 0.337209 sm^3/MWh energywood, 0.32039 sm^3/MWh branches & tops, 0.102326 tonnes/MWh pellets & briquettes, 0.162791 tonnes/MWh waste wood, 0.011628 sm^3/MWh imported energywood and 0.009302 sm^3/MWh imported branches & tops.

[13] As previously explained, it is the L-matrices which contain both direct and indirect requirements

Table 5: The wood requirements matrix (A_{mm}) for Norwegian wood products

Product cat. #	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
1	sm3						0,96	0,96	0,96	0,96	0,96																																								
2	sm3											0,25	0,25		0,81	0,81	0,81	0,81	0,81	0,81										0,21																					
3	sm3																						0,08		0,34																										
4	sm3																								0,32																										
5	sm3																										0,45																								
6	sm3																																																		
7	sm3																																																		
8	sm3						0,08	0,08	0,08	0,08	0,08	0,82	0,82		0,18	0,18	0,18	0,18	0,18	0,18			1,91							0,04																					
9	sm3											0,37	0,37										0,12																												
10	sm3						0,09	0,09	0,09	0,09	0,09																																								
11	sm3																																																		
12	sm3																																																		
13	tonnes																																																		
14	tonnes														0,05	0,05	0,05	0,05	0,05	0,05																															
15	tonnes																					0,63																													
16	tonnes																					0,00																													
17	tonnes																																																		
18	tonnes																					0,15																													
19	tonnes																																																		
20	tonnes																					0,19																													
21	tonnes																																																		
22	tonnes																								0,10			0,53																							
23	tonnes											0,25	0,25										0,02		0,16																										
24	MWh																																																		
25	MWh																																																		
26	MWh																																																		
27	MWh																																																		
28	MWh																																																		
29	GJ																																																		
30	GJ																																																		
31	sm3						0,05	0,05	0,05	0,05	0,05																																								
32	sm3														0,63	0,63	0,63	0,63	0,63	0,63																															
33	sm3														0,21	0,21	0,21	0,21	0,21	0,21																															
34	sm3																								0,01																										
35	sm3																								0,01																										
36	sm3																										0,03																								
37	sm3																																																		
38	sm3																																																		
39	sm3														0,32	0,32	0,32	0,32	0,32	0,32																															
40	sm3																																																		
41	sm3																																																		
42	tonnes																																																		
43	tonnes																					0,00																													
44	tonnes																																																		
45	tonnes																																																		
46	tonnes																					0,02																													
47	tonnes																					0,01																													
48	tonnes																					0,03																													
49	tonnes																																																		
50	tonnes											0,03	0,03																																						

The material balance (also called primal balance) is used to check that the total output (i.e. the x-vector) is equal to total intermediate consumption plus net final demand. The g- and q-vectors are derived directly from the Make and Use tables, and if the requirement matrices are calculated correctly then x_m should equal q and x_n should equal g. By running the mentioned Matlab-file (Appendix A), it can be verified that the material balance is fulfilled here.

Since an objective of this work was to assess the environmental consequences of replacing certain wood products with alternate products and vice versa (i.e. alter the wood flow structure), it was natural to apply the requirements matrix for products (A_{mm}) as the foreground requirements matrix. This made it possible to calculate the total environmental impacts per unit output of each product category (rather than per unit industry output), how these impacts were distributed along the product's value chain and, when considering the overall demand for each product, the total impacts in a given scenario.

3.4 Make & Use tables – Alternative scenario

The wood flow scenario, and subsequent foreground requirements matrix, described so far is a fairly accurate representation of the situation in Norway in the year 2006. From now on, this will be referred to as the 'reference scenario'.

3.4.1 Description of changes

In the alternative scenario developed for this assessment, some rough assumptions were made regarding potential alternatives to disengage a considerable amount of the total annual wood supply. The objective was to create a shift in utilization of the Norwegian wood resources so that the wood currently being used for non-energy purposes could contribute to increasing the share of bioenergy in the domestic energy market. Increasing the annual outtake of Norwegian forests is of course another possibility in order to achieve this, but for this assessment the objective was to evaluate the environmental consequences of a shift in utilization given a fixed resource base.

Given the high quality, and therefore price, on wood used for timber production it was decided that the production levels of these products should be kept unchanged. As a result, only the wooden board- and pulp & paper industries remained as potential wood sources for the bioenergy sector. In the reference scenario these two industries consumed 1’182’000 sm^3 and 4’442’000 sm^3 respectively, making up approximately 44% of the total resource base (12’768’000 sm^3) that year. In the alternative scenario, it was assumed a 50% reduction in production within both industries, making an additional 2’812’00 sm^3 available for use in production of biofuels. That implies that 22% of the total resource base was redistributed.

The reduction in these two wood industries’ production had to be covered by some alternative products in order for the system to be able to meet the fixed demand levels, i.e. both domestic and foreign demand.[14] Domestic gypsum board production was increased correspondingly to the reduction in domestic wood production, applying an assumed gypsum board density of 0.6 tonnes/sm^3 and assuming that gypsum boards can replace both fibre- and particle boards. In order to cover the reduction in Norwegian pulp and paper production, foreign pulp and paper production was increased.

The wood that became available in the Norwegian sector after performing these changes was then sent to bioethanol production (1’058’000 sm^3), pellets & briquettes production (560’500 sm^3) and waterborne bio-based heat production (1’195’500 sm^3). This resulted in production increases of these products with factors of 9.82, 3.79 and 3.07 respectively. The additional bioethanol was used to replace gasoline, while the heat products (i.e. heat_pellts&briquettes and heat_waterborne_bio) were used to replace heat production based on oil. The new Make and Use tables, as well as the new A_{mm} matrix, are shown below.

[14] Although total export was kept fixed, a different distribution between export of domestic products and ’export of foreign products’ (i.e. foreign products consumed outside Norway) were in some cases required in order maintain balance in the Make & Use tables

Table 6: Make table (M) for Norwegian wood products sector in the alternative scenario

Product	Unit	NFOR	SAWMIL	PULPPR	PAPPR	WBRDPR	GYPSPR	PELBRIPR	RECOV	BETHANPR	GASOLPR	HPRWBB	HPRWBO	HPRLOG	HPRPEL	HPROIL	IMP	FDD	EXP	Sum
ST	sm3	4590000																		4590000
PW	sm3	4000000																		4000000
EW	sm3	152000																		152000
BRAT	sm3	138000																		138000
FW	sm3	2950000																		2950000
SAWNT	sm3		700000																	700000
PLNDT	sm3		1500000																	1500000
CHIP	sm3		1500000																	1500000
SAWD	sm3		340000																	340000
BARK	sm3		458000																	458000
FBRD	sm3					96500														96500
PBRD	sm3					191000														191000
GYPS	tonnes						288000													288000
BARK2	tonnes			64000																64000
MPULP	tonnes			718500																718500
CTMP	tonnes			49500																49500
SCPULP	tonnes			12000																12000
SULPHA	tonnes			293000																293000
SULPHI	tonnes			79000																79000
RECPAP	tonnes								670000											670000
PAPER	tonnes				1054500															1054500
PELBRI	tonnes							352500												352500
RECW	tonnes								934000											934000
HWBB	MWh											1318000								1318000
HWBO	MWh												1610000							1610000
HLOG	MWh													6500000						6500000
HPELBRI	MWh														516500					516500
HOIL	MWh															4615500				4615500
BETHAN	GJ									4712000										4712000
GASOL	GJ										59868000									59868000
IMPST	sm3																240000			240000
IMPPW1	sm3																1530000			1530000
IMPPW2	sm3																500000			500000
IMPEW	sm3																5000			5000
IMPBRAT	sm3																4000			4000
IMPFW	sm3																175000			175000
IMPSAWNT	sm3																598000			598000
IMPPLNDT	sm3																364000			364000
IMPCHIP	sm3																390500			390500
IMPFBRD	sm3																192000			192000
IMPPBRD	sm3																101000			101000
IMPGYPS	tonnes																35000			35000
IMPMPULP	tonnes																58000			58000
IMPCTMP	tonnes																47500			47500
IMPSCPULP	tonnes																12000			12000
IMPSULPHA	tonnes																178500			178500
IMPSULPHI	tonnes																94000			94000
IMPRECPAP	tonnes																30000			30000
IMPPAPER	tonnes																1662500			1662500
IMPRECW	tonnes																15000			15000

Table 7: Use table (U) for Norwegian wood products sector in the alternative scenario

Product	Unit	NFOR	SAWMIL	PULPPR	PAPPR	WBRDPR	GYPSPR	PELBRIPR	RECOV	BETHANPR	GASOLPR	HPRWBB	HPRWBO	HPRLOG	HPRPEL	HPROIL	IMP	FDD	EXP	Sum
ST	sm3		4340000																250000	4590000
PW	sm3			986500		71500				1158000								1314000	470000	4000000
EW	sm3							7000				145000								152000
BRAT	sm3											138000								138000
FW	sm3													2945000					5000	2950000
SAWNT	sm3																	278000	422000	700000
PLNDT	sm3																	1458000	42000	1500000
CHIP	sm3		370000	219500		235000		632500		20000									23000	1500000
SAWD	sm3					105000		116000										85000	34000	340000
BARK	sm3		383000															75000		458000
FBRD	sm3																	35500	61000	96500
PBRD	sm3																	86000	105000	191000
GYPS	tonnes																	288000		288000
BARK2	tonnes			64000																64000
MPULP	tonnes				661000														57500	718500
CTMP	tonnes				2000														47500	49500
SCPULP	tonnes																		12000	12000
SULPHA	tonnes				154500														138500	293000
SULPHI	tonnes																		79000	79000
RECPAP	tonnes				204500														465500	670000
PAPER	tonnes																	282000	772500	1054500
PELBRI	tonnes											44000			275500				33000	352500
RECW	tonnes					71500		2000				141500						437000	282000	934000
HWBB	MWh																	1318000		1318000
HWBO	MWh																	1610000		1610000
HLOG	MWh																	6500000		6500000
HPELBRI	MWh																	516500		516500
HOIL	MWh																	4615500		4615500
BETHAN	GJ																	4232000	480000	4712000
GASOL	GJ																	59868000		59868000
IMPST	sm3		240000																	240000
IMPPW1	sm3			765000								765000								1530000
IMPPW2	sm3			250000								250000								500000
IMPEW	sm3											5000								5000
IMPBRAT	sm3											4000								4000
IMPFW	sm3													175000						175000
IMPSAWNT	sm3																	598000		598000
IMPPLNDT	sm3																	364000		364000
IMPCHIP	sm3			390500																390500
IMPFBRD	sm3																	129000	63000	192000
IMPPBRD	sm3																		101000	101000
IMPGYPS	tonnes																	35000		35000
IMPMPULP	tonnes				500														57500	58000
IMPCTMP	tonnes																		47500	47500
IMPSCPULP	tonnes																		12000	12000
IMPSULPHA	tonnes				24000														154500	178500
IMPSULPHI	tonnes				9000														85000	94000
IMPRECPAP	tonnes				30000															30000
IMPPAPER	tonnes																	604000	1058500	1662500
IMPRECW	tonnes					7500						7500								15000

Table 8: The requirement matrix (A_{mm}) for Norwegian wood products in the alternative scenario

Product cat. #	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
1	sm3						0,96	0,96	0,96	0,96	0,96																																								
2	sm3											0,25	0,25		0,81	0,81	0,81	0,81	0,81	0,81										0,25																					
3	sm3																						0,02		0,11																										
4	sm3																								0,10																										
5	sm3																										0,45																								
6	sm3																																																		
7	sm3																																																		
8	sm3						0,08	0,08	0,08	0,08	0,08	0,82	0,82		0,18	0,18	0,18	0,18	0,18	0,18			1,79																												
9	sm3											0,37	0,37										0,33																												
10	sm3						0,09	0,09	0,09	0,09	0,09																																								
11	sm3																																																		
12	sm3																																																		
13	tonnes																																																		
14	tonnes														0,05	0,05	0,05	0,05	0,05	0,05																															
15	tonnes																					0,63																													
16	tonnes																					0,00																													
17	tonnes																																																		
18	tonnes																					0,15																													
19	tonnes																																																		
20	tonnes																					0,19																													
21	tonnes																																																		
22	tonnes																								0,03			0,53																							
23	tonnes											0,25	0,25										0,01		0,11																										
24	MWh																																																		
25	MWh																																																		
26	MWh																																																		
27	MWh																																																		
28	MWh																																																		
29	GJ																																																		
30	GJ																																																		
31	sm3						0,05	0,05	0,05	0,05	0,05																																								
32	sm3														0,63	0,63	0,63	0,63	0,63	0,63					0,58																										
33	sm3														0,21	0,21	0,21	0,21	0,21	0,21					0,19																										
34	sm3																																																		
35	sm3																																																		
36	sm3																										0,03																								
37	sm3																																																		
38	sm3																																																		
39	sm3														0,32	0,32	0,32	0,32	0,32	0,32																															
40	sm3																																																		
41	sm3																																																		
42	tonnes																																																		
43	tonnes																																																		
44	tonnes																																																		
45	tonnes																																																		
46	tonnes																					0,02																													
47	tonnes																					0,01																													
48	tonnes																					0,03																													
49	tonnes																																																		
50	tonnes											0,03	0,03												0,57																										

3.5 Establishing the A_{bf} and F_f matrices

In general, both the foreground system's requirements for inputs from the background system (A_{bf}) and its direct emissions (F_f) were modeled based on already existing process datasets found in the Ecoinvent v2.2 database from 2010. However, some modifications (described below) to these datasets were made in order to make them more representative to Norwegian conditions.

3.5.1 Electricity and transport requirements

It is widely recognized that energy requirements, in the form of heat, power and transportation, normally constitute the main contribution to environmental impacts in a system. Therefore, these were the main focus areas in the data modification process in this work. First of all, all electricity inputs in the datasets were changed to a Norwegian electricity mix. One possibility was to run the assessments using the standard Ecoinvent dataset for Norwegian electricity *'electricity, medium voltage, at grid/ NO/ kWh',* representing both domestically produced electricity and imported electricity. However, this mix does not consider the trade of renewable energy certificates, so-called Guarantees of Origin and RECS certificates. Norway is net exporter of such certificates (Norwegian Water Resources and Energy Directorate, 2011), so when taking the trade of these into account, the Norwegian consumption mix quickly becomes more 'dirty', even though the production mix stays the same. This adjusted consumption mix is the one applied by the Norwegian Water Resources and Energy Directorate in their annual product declaration for Norwegian electricity. Their latest declaration (i.e. 2009) was used in this work and consists of: 46.9% hydro power, 0.5% wind power, 4.2% heat power (in this work assumed to be gas fired), 5.7% imports and 42.8% of unknown origin. For this unknown origin portion, it was assumed here that it would be similar to the European consumption mix. Furthermore, it is assumed that none of modeled industries buy renewable energy certificates for themselves, i.e. they are all given the mix described above. The issue of whether or not renewable energy certificates should be considered in environmental assessments will be given further attention in the discussion section.

For the actual heat and electricity requirements of the biggest wood industries (i.e. the sawmill industry, the pulp and paper industry and the wooden board industry), the Ecoinvent data were compared to other sources. Environmental declarations from major Norwegian plants were used as secondary sources for both the sawmill- (Moelven Van Severen AS, 2009) and wooden board industries (Forestia, 2009). A 'Best Available Techniques' (BAT) document issued by the European Commission (2001) for the pulp and paper industry served as a credible secondary source for this industry. For both the sawmill- and wooden board industry, the numbers from both sources matched relatively well and the Ecoinvent datasets were therefore not changed.

Ecoinvent process data for the pulp and paper industry also appeared to be in reasonable accordance with the information found in the BAT-document. However, the Ecoinvent datasets on paper are modeled based on an assumption of integrated paper mills, i.e. production of pulp and paper takes place at the same location. As a result of this, the Ecoinvent datasets on paper contain the entire process from input materials (via pulp) to final paper products, making it difficult to understand which inputs and emissions are linked to the pulp making process and which are linked to the paper making process. In this assessment it was necessary to separate the production of pulp and paper as these are separate processes in the foreground system. In other words, new datasets for domestic paper production were required. This was done by comparing the Ecoinvent datasets for pulp and paper, respectively, and then establish new datasets for domestic paper where the inputs and emissions in the pulp datasets were left out. As these inputs and emissions already are included via the foreground requirements matrix (i.e. the paper industry's demand for pulp) it was important to avoid double-counting. Due to this need for new modeling, data from the BAT-document was on a few occasions used to supplement the Ecoinvent datasets whenever the information embedded in these proved insufficient to establish the new datasets. Even more importantly it was used to check that the numbers in the new datasets made sense, i.e. that they where in the right range.

Although there are many types of paper (and cardboard), paper is in this analysis defined as a single product category. This was necessary in order to avoid further confusion and complexity in the modeling work for this industry. According to the derived requirements matrices for wood products in Norway (A_{mm}), the total paper production in Norway is made up of approximately 60% mechanical pulp, 20% chemical pulp and 20% deinked pulp (i.e.

pulp from recycled paper). Consequently, these three paper production processes made up the new domestic paper datasets.

As for transportation, Norwegian specific transportation data on saw timber was found in a working paper from the MIKADO research project (Flæte, 2009, p.11). Saw timber and pulp wood are normally transported separately due to different locations of the consuming industries (i.e. sawmills versus pulp factories). Through personal communication with Per Otto Flæte at Treteknisk Institutt, it was suggested that the corresponding average transport distance for pulp wood was a few kilometers higher and was therefore set to 115 km. The average transport distance of raw materials to pellets- and briquettes production was assumed to be 10 km since such plants often are located close to their main supplier (e.g. a sawmill). When no country specific data was available, the transport inputs were not changed.

All transportation in this analysis is assumed to be road transportation, i.e. transport by train and boat is neglected. This is done in order to ensure a fair comparison between the different products, although it might lead to slightly different environmental impacts than the actual situation represents.

3.5.2 Other modifications to existing LCA data

Since all wood inputs in this model is included via the foreground system, such inputs had to be removed from the datasets used in the A_{bf} matrix in order to avoid double-counting.

Fertilizer inputs in forestry activities were also removed from the raw wood datasets as fertilizing is rarely used in Norwegian forest management (Flæte, 2009, p.16). For simplicity, it was assumed that all chipping of energywood and forestry residues takes place in mobile chippers in the forest.

For bioethanol production all process data was taken from the supplementary material for the article '*Life cycle assessment of second generation bio-ethanols produced from Scandinavian boreal forest resources: A regional analysis for Middle Norway*' (Bright et al., 2009b). The thermochemical ('best case scenario') production process described there was chosen as model for bioethanol in this work. Since the numbers presented in the article were referred to functional units of 1 kg produced bioethanol and 1 km covered by bioethanol use (assuming

0.0616 liter/km), conversion factors of 0.0268 GJ/kg and 0.789 kg/liter were applied to convert the data into a functional unit of 1 GJ. For comparison, conversion factors of 0.0438 GJ/kg and 0.737 kg/liter were used to convert the gasoline datasets into a functional unit of 1 GJ. The conversion efficiencies for the different type of engines in the use phase were not considered.

For waterborne heating systems there is a loss of approximately 10% in the distribution network (Statistics Norway, 2011a). This was considered in this assessment, but the infrastructure of the distribution system was not included due to lack of data and expected low significance. For the 'non-biofueled' share of waterborne heating (i.e. heat_waterborne_other) it was assumed that 80% of the heat is produced from burning of domestic waste, and 10% from oil and natural gas each (Statistics Norway, 2011b).

Regarding the imported product categories, transport to Norway was excluded in this analysis. The reason for this is simply that when creating alternative scenarios, where e.g. more paper is produced outside Norway in order to make up for a reduced Norwegian export, these inputs would have created a false impression of the differences between domestic and foreign products. It should also be noted that even though these product categories have the 'imported' label, in an alternative scenario they don't necessarily represent actual imports, but rather products produced outside Norway in order to cover demand outside Norway as a result of reduced domestic production.

3.6 Establishing the A_{bb} and F_b matrices

The background system (A_{bb} and F_b) is automatically included via the A_{bf} datasets' interactions with the Ecoinvent v2.2 database.

3.7 Establishing the demand vectors (Y)

The perhaps most important quality of the model presented above is the capacity to realistically describe the situation within the Norwegian wood products sector, and thereby facilitate accurate scenario analyses of the 'overall picture', i.e. the sum of demand for wood products and their alternatives. However, it also holds the possibility to zoom in on the various industries and products. In order to illustrate the various possibilities embedded in the model, assessments on three different levels were carried out during this project.

First, an assessment of the ‘overall picture’ was performed. This is later referred to as the national level. In this case, both Norwegian demand for imports as well as foreign demand for Norwegian exports were included. This was necessary in order to ensure a fair comparison between different scenarios. Otherwise, if e.g. foreign demand for Norwegian products were neglected, Norway could easily reduce its paper production considerably (e.g. to increase the share of bioenergy) and the amount of paper produced elsewhere (i.e. imported paper) would not have to be increased to cover the defined demand. In turn, this would create a situation where conclusions would be made based on what would be best from a Norwegian ‘consumption perspective [15], and not for the global society. Since many environmental issues such as climate change are global problems, it was desirable in this work to assess what would be the best scenario as seen from a ‘global perspective’.

Then, an assessment of only the production, caused by foreign and domestic demand, of Norwegian wood products was carried out (i.e. sector level). The intentions of this assessment were to calculate the overall impact of this sector alone, as well as finding out which industries represent the biggest impacts within the sector. Consequently, it did not include the production of alternative products, nor the final combustion of wood products for heat and transportation. In other words, the system was here defined as a cradle-to-gate system.

For both the national- and sector assessments, the demand placed upon the system was the sum of final domestic demand (FDD) and exports (EXP), which is shown in the respective Use tables for each scenario (table 4 and table 7). The only exceptions from this are the 1’314’000 cubic meters of pulpwood and 437’000 tonnes of post consumer recovered wood which are embedded in the FDD in order to balance the Make and Use tables, but in reality are going to storage and landfills respectively. Since these flows can be considered to not be a part of the demand in the given year they were removed from the demand vectors.

Finally, individual product assessments of various wood based end-products were performed in order to study how the impacts were distributed along their respective value chains (i.e.

[15] By a ’consumption perspective’ it is meant that each country is responsible for the emissions linked to its consumption, i.e. imports and domestic production to cover own demand, but not exports

product level). For these assessments an external demand of 1 was placed on the respective product in order to get results per functional unit.

4 RESULTS AND ANALYSIS

Here, a selection constituting the most interesting assessment results are presented and analyzed. First, Sankey diagrams on the wood flows in both scenarios are shown in order to give a clear overview of the aggregated wood consumption by the various industries. Then, the assessment results are presented for the three previously explained levels (section 3.7), i.e. national-, sector- and product level. Some of the most important observations from the results are commented and explained where possible.

4.1 Wood flow analysis

The Sankey diagrams below illustrate how the total amount of wood resources is distributed for different purposes in the two scenarios. The diagrams are compiled based on the numbers in the Make & Use tables shown in section 3. All flows are given in 1000 cubic meters.

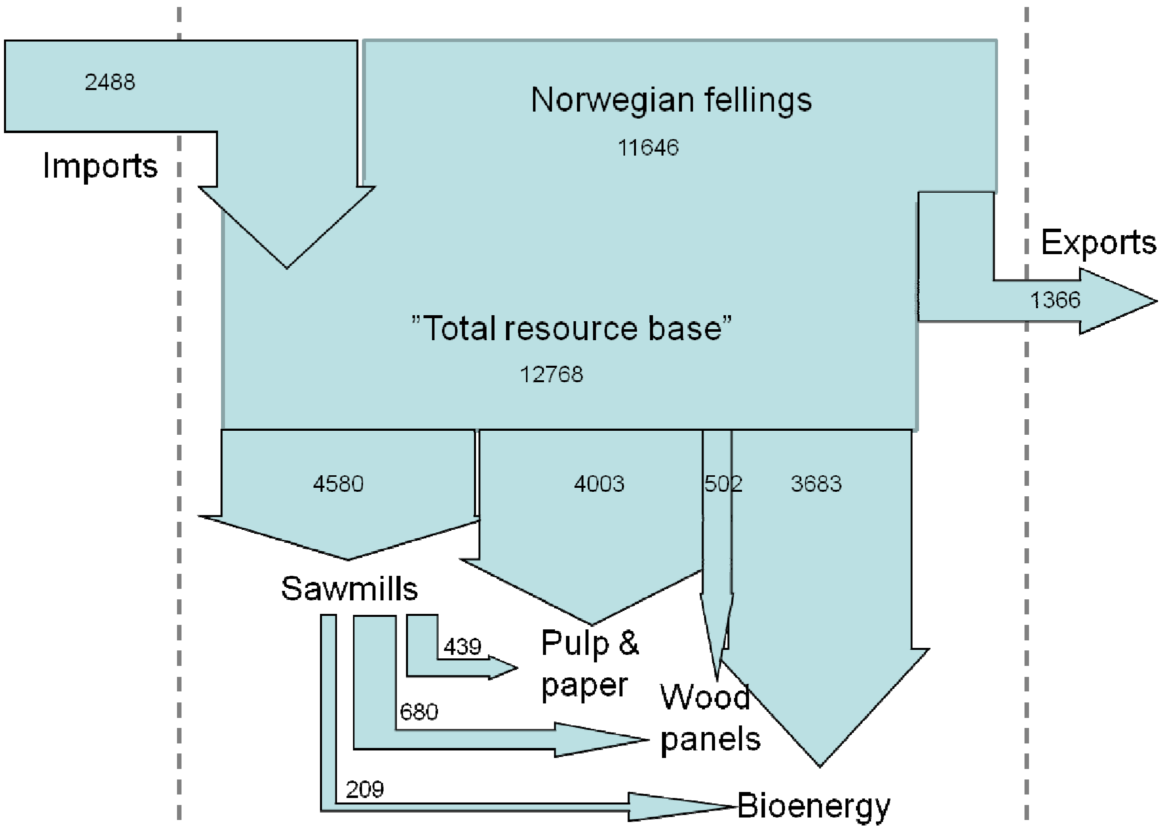

Figure 3: Sankey diagram for major wood flows (1000 sm^3) in the reference scenario (Norway 2006)

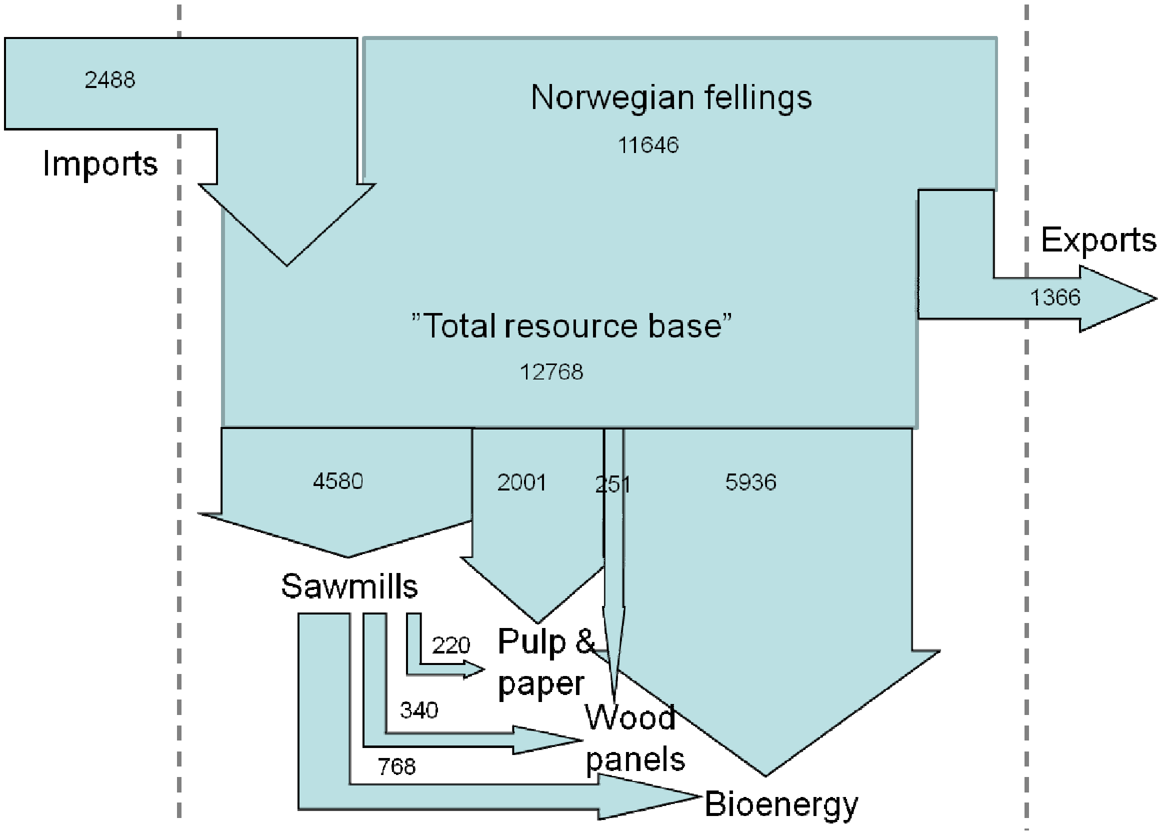

Figure 4: Sankey diagram for major wood flows (1000 sm3) in the alternative scenario

The distribution of industrial residues (i.e. chips and sawdust) from the sawmills is also included in the diagrams. Post consumer recovered wood is considered to be a part of the total resource base, and is converted from tonnes to sm^3 by applying the assumed density of 0.44 tonnes/sm^3. For both recovered wood and pulpwood, the respective amounts assumed to be going to landfills (993'000 sm^3 recovered wood) and storage (1'314'000 sm^3 pulpwood) are excluded in this overview as they are not consumed by any of the sectors. As previously mentioned, approximately 22% of the total resource base was redistributed in the alternative scenario.

Table 9: Final wood consumption in sm^3

Industry	Final wood consumption		Relative share of total wood resource base	
	Reference scenario	Alternative scenario	Reference scenario	Alternative scenario
Sawmills	3252000	3252000	25 %	25 %
Pulp & paper	4442000	2221000	35 %	17 %
Wood panels	1182000	591000	9 %	5 %
Bioenergy	3892000	6704000	30 %	53 %
SUM	12768000	12768000	100 %	100 %

The table above shows the final and relative wood consumption of the four wood consuming industries in both scenarios. In the alternative scenario, more than half of the total wood resources base is used for bioenergy purposes, while both the pulp & paper- and wood panels industry have reduced their consumption of wood by 50% as a result of a 50% reduction in production.

4.2 Results at national level

As described in section 3.7, the complete demand vectors (i.e. all product categories) for the given scenarios were applied in this part of the assessment. The resulting total impacts vectors (d) may not be very interesting by themselves as the defined system only consists of some few additional products outside the Norwegian wood products sector, i.e. they give neither a complete picture of the total economy nor are they confined to the wood products sector (the latter is treated in section 4.3). However, it is reminded that the intention behind the selection of product categories was to arrange for a fair comparison between the two scenarios, when final demand is fixed but the product mix covering demand is rearranged. For this purpose, the presented results can provide useful information on the environmental characteristics of the system.

In order to arrange for easy comparison of the scenarios, the results for this part of the assessment is broken down on aggregated end-product categories. This means that those of the previously defined product categories considered to be end-products[16] are re-arranged into aggregated end-product categories as shown in the table below.

Table 10: Rearrangement of original product categories into aggregated categories

Aggregated categories	Original categories
Construction wood	Sawn timber (not planed), Planed timber, Imported sawn timber (not planed), Imported planed timber
Wooden boards	Fibre boards, Particle boards, Imported fibre boards, imported particle boards
Gypsum boards	Gypsum boards, Imported gypsum boards
Domestic paper	Paper and cardboard
Foreign paper	Imported paper and cardboard
Heat from wood	Heat_waterborne_bio, Heat_logs, Heat_pellets&briquettes
Heat from other sources	Heat_waterborne_other, Heat_oil
Bioethanol	Bioethanol
Gasoline	Gasoline
Other	Sawdust, bark
Export	All raw- and intermediate wood products produced to cover foreign demand

[16] Note than since heat can be considered to be an end-product in this system, other products such as e.g. pellets & briquettes are considered to be intermediate products

It should be noted that the use phase of the transportation fuels (i.e. combustion in vehicle engines) is included in the results. This was necessary in order to ensure a more fair comparison between bioethanol and gasoline. The aggregated category 'Other' only includes the impacts resulting from the external demand for sawdust and bark. The remaining impacts caused by these products, as a result of internal demand, are allocated onto the respective product category according to its share of the impacts.

For the national level assessments all environmental impact categories of the ReCiPe (H) method are presented.

4.2.1 Relationship between the national level scenario results

As shown in table 11, the relative differences in total impacts were quite small for most impact categories. A positive number in the columns showing the difference indicates a higher impact in the alternative scenario, and vice versa.

Table 11: The total environmental impacts at national level

Environmental impact category	Unit	Reference scenario	Alternative scenario	Absolute difference	Relative difference
agricultural land occupation/ RER/ (H)	m2a	5,79E+10	6,48E+10	6,97E+09	12,0 %
climate change/ GLO/ (H)	kg CO2-Eq	1,41E+10	1,38E+10	-2,85E+08	-2,0 %
fossil depletion/ GLO/ (H)	kg oil-Eq	3,85E+09	3,60E+09	-2,47E+08	-6,4 %
freshwater ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	5,50E+07	5,25E+07	-2,46E+06	-4,5 %
freshwater eutrophication/ RER/ (H)	kg P-Eq	2,29E+06	2,21E+06	-8,14E+04	-3,6 %
human toxicity/ RER/ (H)	kg 1,4-DCB-Eq	4,36E+09	4,22E+09	-1,42E+08	-3,3 %
ionising radiation/ RER/ (H)	kg U235-Eq	1,75E+09	2,09E+09	3,39E+08	19,3 %
marine ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	5,89E+07	5,57E+07	-3,23E+06	-5,5 %
marine eutrophication/ RER/ (H)	kg N-Eq	9,77E+06	9,33E+06	-4,35E+05	-4,5 %
metal depletion/ GLO/ (H)	kg Fe-Eq	1,71E+08	1,78E+08	6,49E+06	3,8 %
natural land transformation/ RER/ (H)	m2	8,05E+06	8,62E+06	5,69E+05	7,1 %
ozone depletion/ GLO/ (H)	kg CFC-11-Eq	6,72E+02	6,42E+02	-2,97E+01	-4,4 %
particulate matter formation/ RER/ (H)	kg PM10-Eq	1,54E+07	1,55E+07	4,34E+04	0,3 %
photochemical oxidant formation/ RER/ (H)	kg NMVOC	3,92E+07	3,91E+07	-7,42E+04	-0,2 %
terrestrial acidification/ RER/ (H)	kg SO2-Eq	4,25E+07	4,15E+07	-1,01E+06	-2,4 %
terrestrial ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	1,43E+07	1,38E+07	-4,98E+05	-3,5 %
urban land occupation/ RER/ (H)	m2a	7,58E+08	8,68E+08	1,10E+08	14,6 %
water depletion/ GLO/ (H)	m3	4,79E+07	4,53E+07	-2,53E+06	-5,3 %

Even though the relative differences are quite small, due to a large system with huge environmental impacts, there is a considerable decrease in most impact categories in the alternative scenario. For instance, there is a reduction in climate change impacts of 285 kilo tonnes CO_2 equivalents. If we let the Ecoinvent v2.2 process dataset *'operation, passenger car, petrol, fleet average 2010/km/RER'* represent the emissions from an average car running on gasoline (e.g. CO_2 emission rate of approximately 187 g/km), and multiply this with the average yearly driving distance of a Norwegian passenger car in 2009 equal to 13'439 km

(Statistic Norway, 2011d), we get that this reduction corresponds to the annual emissions of roughly 88’000 cars.

The raw material behind the presented results further indicated that the reduction would have been close to 645 kilo tonnes CO_2 equivalents if the traditional approach of excluding biogenic carbon had been applied. This difference illustrates the significance of including the climate change (CC) impacts from biogenic CO_2 and CH_4 in life cycle assessments.

The reduction in overall CC impacts is a result of the following changes:

- ✓ 4’232’000 GJ of gasoline replaced with bioetahnol (i.e. a reduction of 146 kt CO_2-eq.)
- ✓ 287’500 sm^3 of wooden boards replaced with gypsum boards (i.e. a reduction of 61 kt CO_2-eq.)
- ✓ 1’384’500 MWh of heat_oil replaced with heat_WB_bio and heat_pellets&briquettes (i.e. a reduction of 138 kt CO_2-eq.)

The substitutions contributing to an increase in CC impacts are the additional foreign pulp- and paper production instead of domestic pulp- and paper production, but this increase is quite small (i.e. an increase of approximately 60 kt CO_2-eq.). As this is a small number compared to the drastic substitution factor in this industry (i.e. 50%), it indicates that foreign- and domestic paper had approximately the same climate change impacts in this assessment. This is confirmed by the product assessment results in sector 4.4 (see table 13).

It is unclear why the increases in agricultural land occupation-, natural land transformation- and urban land occupation impacts are relatively big. Since standing wood is the dominant contributor to these impacts in this system, and the two scenarios should have approximately the same consumption of wood, this huge difference seems unlikely. One possible reason could be a potential modeling error in the datasets for Norwegian- and foreign wood (used in foreign paper production), leading to an unfair comparison of the two types of wood. However, since this potential error most likely lies within the respective paper production processes’ requirement for wood and/or within the wood datasets themselves, neither of which are of great significance to the remaining impact categories, it should not seriously influence the credibility of the overall results.

The increase in ionising radiation is probably due to the increase in use of European electricity, which has a relatively large share of nuclear energy, as a result of more foreign paper production in the alternative scenario.

4.2.2 Breakdown of environmental impacts in the reference scenario

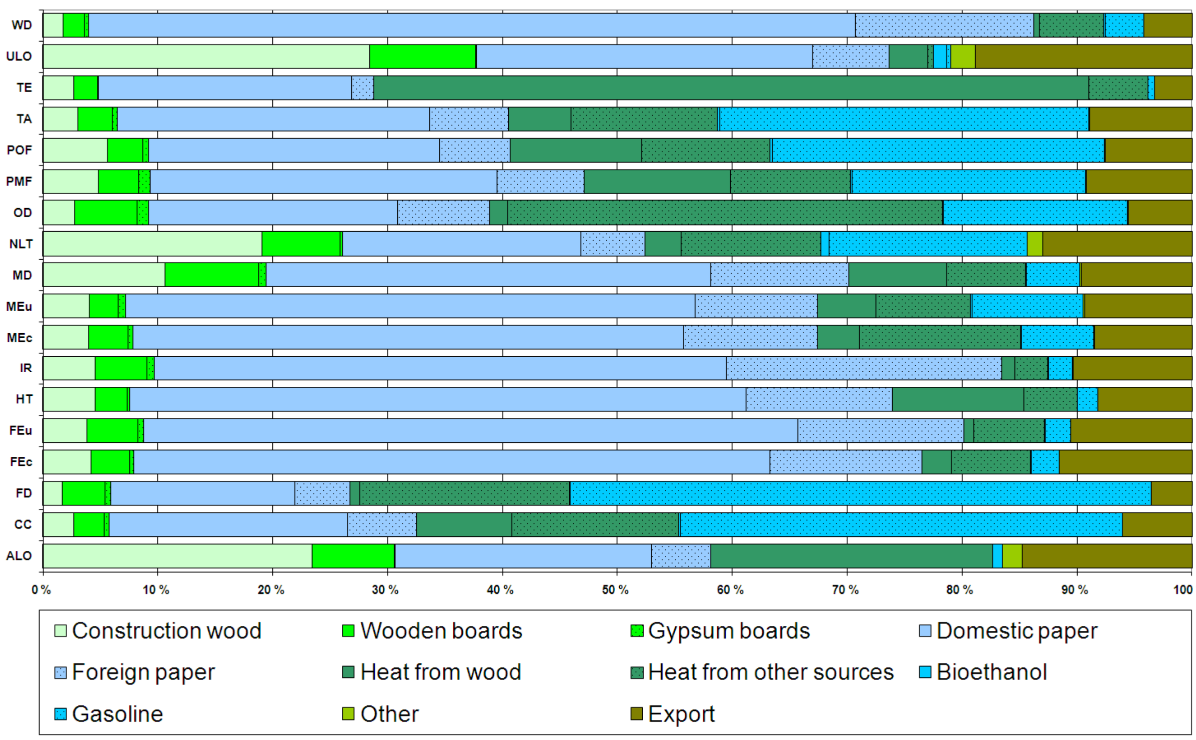

Figure 5: Breakdown of environmental impacts in the reference scenario

In general, the results show that the demands for paper, heat and transportation fuels are the dominating contributors to most of the impact categories. With the exception of some impact categories (including climate change), paper is the biggest of the three, probably due the large amounts of chemicals used in the pulping- and papermaking process.

For climate change, gasoline is not surprisingly by far the biggest contributor, followed by heat from non-wood sources and paper. All these product categories emit large amounts of CO_2 during either the production (e.g. pulp- and paper production) and/or use phase (e.g. combustion of gasoline and combustion of fossil fuels for heat production). An interesting observation is the link between fossil depletion (FD) and climate change (CC) who have quite similar distribution profiles. This says something about the correlation between fossil energy use and global warming impacts.

Agricultural land occupation (ALO), natural land transformation (NLT) and urban land occupation (ULO) all have significant contributions from construction wood as well. This is surely due the sawmills' high consumption of wood.

4.2.3 Breakdown of environmental impacts in the alternative scenario

It is reminded that in this scenario the 'Export' category does not only represent physical export from Norway, but also production occuring elsewhere in order to cover foreign demand as a result of reduced Norwegian production.

The distribution of impacts shown in figure 6 is presented relative to the total impacts in the reference scenario.

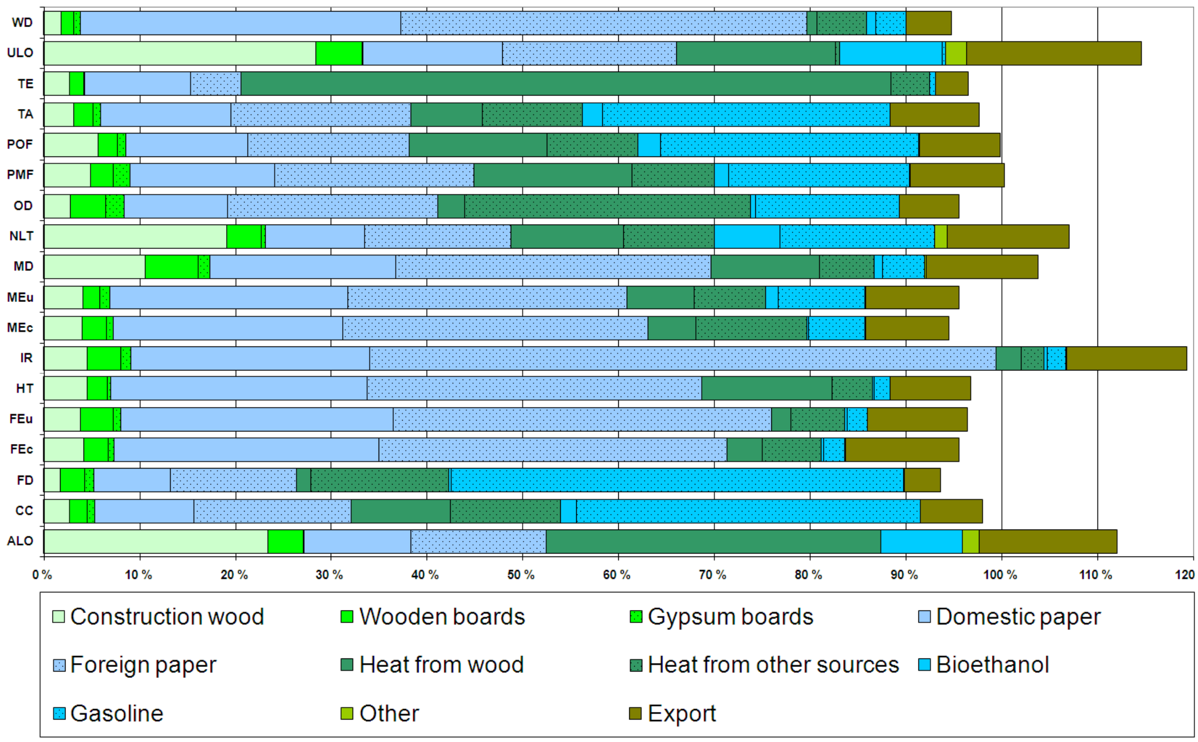

Figure 6: Breakdown of environmental impacts in the alternative scenario

As the diagram above shows, the situation with respect to distribution very much resembles the one in the reference scenario. However, foreign paper naturally represents a bigger share of the total impacts from paper production than before. Correspondingly, heat from wood represents a bigger share of the impacts from heat production. Similar observations can be made for wooden boards (i.e. smaller share of impacts from total board production) and bioethanol (i.e. bigger share of impacts from transportation fuels).

4.3 Results at sector level

In this part of the assessment, only the industries producing wood products were considered, i.e. forestry, sawmills and woodworking industries, pulp industry, paper industry, wooden boards production, pellets- and briquettes production and bioethanol production. The intention was to show how the total environmental impacts from this sector are distributed between the various industries in the Norwegian wood products sector, and how this distribution would change in the alternative scenario. The new system boundaries imply that e.g. the following aspects are not included in the results: combustion of wood in order to produce heat, the use of bioethanol and various production activities outside of Norway. [17]

The impacts associated with biofuels taken directly from the forest (i.e. firewood, energywood and forestry residues) are here included in the 'Forestry' category, not in 'Biofuel production'. The 'Import' category represents only the impacts embodied in wood imports going into the Norwegian wood products sector as input materials (e.g. industrial residues), not import of final products such as e.g. timber (as these are not considered in the sector assessment).

As for the national level assessment above, results for all environmental impact categories are presented.

4.3.1 Relationship between the sector level scenario results

At the sector level, the relative differences in total impacts for the two scenarios were quite big for most impact categories. As before, a positive number in the columns showing differences indicates a higher impact in the alternative scenario, and vice versa.

[17] Foreign raw- and intermediate wood products used as input materials in Norwegian production is naturally included.

Table 12: The total environmental impacts at sector level

Environmental impact category	Unit	Reference scenario	Alternative scenario	Absolute difference	Relative difference
agricultural land occupation/ RER/ (H)	m2a	5,23E+10	4,87E+10	-3,60E+09	-6,9 %
climate change/ GLO/ (H)	kg CO2-Eq	4,31E+09	2,52E+09	-1,79E+09	-41,6 %
fossil depletion/ GLO/ (H)	kg oil-Eq	8,95E+08	5,01E+08	-3,94E+08	-44,0 %
freshwater ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	3,93E+07	2,09E+07	-1,84E+07	-46,8 %
freshwater eutrophication/ RER/ (H)	kg P-Eq	1,64E+06	8,68E+05	-7,72E+05	-47,1 %
human toxicity/ RER/ (H)	kg 1,4-DCB-Eq	2,91E+09	1,56E+09	-1,36E+09	-46,6 %
ionising radiation/ RER/ (H)	kg U235-Eq	1,15E+09	6,26E+08	-5,21E+08	-45,4 %
marine ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	3,59E+07	1,93E+07	-1,67E+07	-46,4 %
marine eutrophication/ RER/ (H)	kg N-Eq	6,25E+06	3,45E+06	-2,80E+06	-44,8 %
metal depletion/ GLO/ (H)	kg Fe-Eq	1,06E+08	6,35E+07	-4,23E+07	-40,0 %
natural land transformation/ RER/ (H)	m2	4,86E+06	4,29E+06	-5,70E+05	-11,7 %
ozone depletion/ GLO/ (H)	kg CFC-11-Eq	2,22E+02	1,28E+02	-9,40E+01	-42,3 %
particulate matter formation/ RER/ (H)	kg PM10-Eq	7,09E+06	4,08E+06	-3,01E+06	-42,5 %
photochemical oxidant formation/ RER/ (H)	kg NMVOC	1,56E+07	9,50E+06	-6,13E+06	-39,2 %
terrestrial acidification/ RER/ (H)	kg SO2-Eq	1,73E+07	9,66E+06	-7,63E+06	-44,1 %
terrestrial ecotoxicity/ RER/ (H)	kg 1,4-DCB-Eq	4,02E+06	2,15E+06	-1,87E+06	-46,5 %
urban land occupation/ RER/ (H)	m2a	6,68E+08	6,04E+08	-6,45E+07	-9,6 %
water depletion/ GLO/ (H)	m3	3,50E+07	1,85E+07	-1,66E+07	-47,3 %

We can see that almost all impact categories have been reduced by 40-50% in the alternative scenario, mainly because of the 50% reduction in domestic pulp & paper production. Of course, the reduction in wooden boards production has also contributed to this, while the increase in bioethanol production has had a small counter-active effect.

The overall impacts for the three impact categories dominated by domestic forestry activities (i.e. ULO, NLT and ALO) have remained relatively constant as the total output (i.e. overall felling) from this industry is the same in both scenarios. The reason for the small reduction (~ 10%) is the reduced need for imported wood to the pulp industry. In the alternative scenario, this wood is utilized in waterborne heat production instead, which falls outside the system defined in this part of the assessment.

4.3.2 Breakdown of environmental impacts in the reference scenario

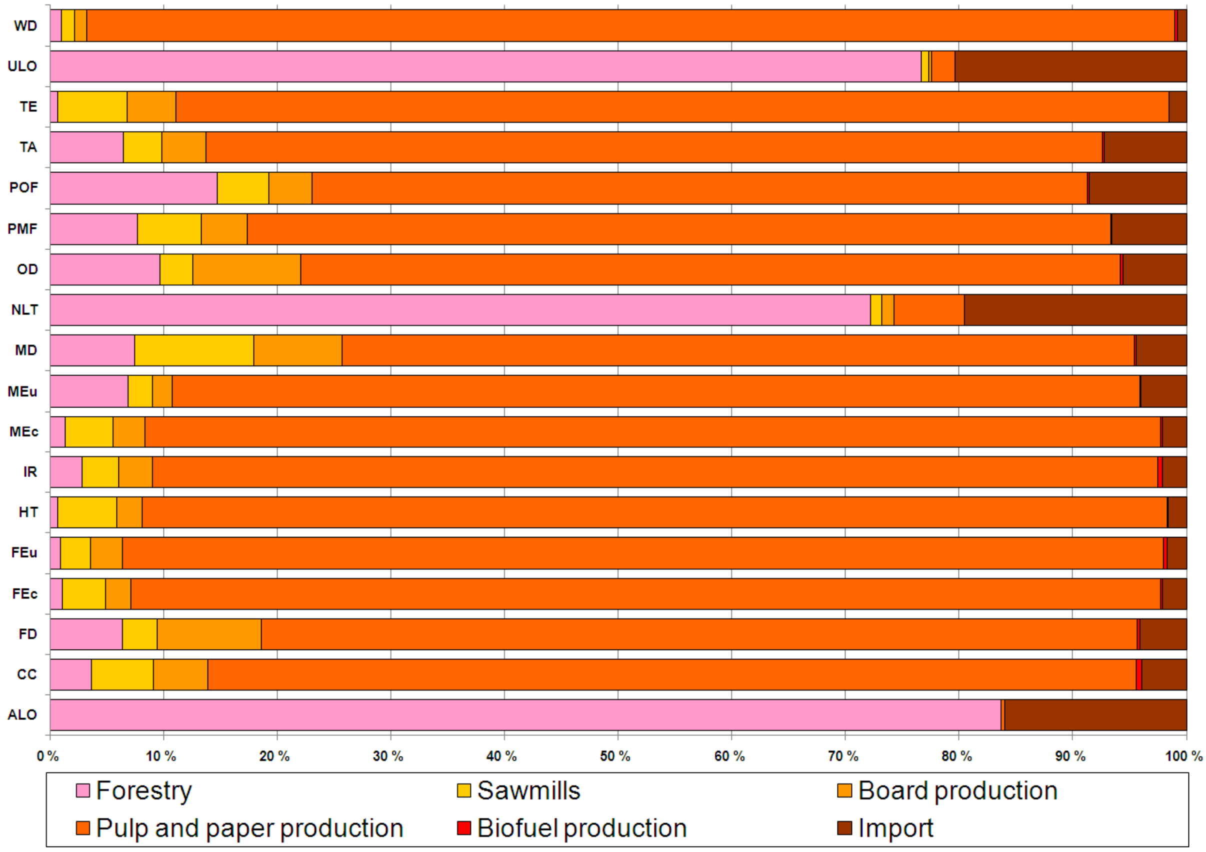

Figure 7: Breakdown of environmental impacts within the Norwegian wood products sector in the reference scenario

The results show that pulp & paper production is clearly the dominant contributor to most environmental impact categories in the Norwegian wood products sector. Since the impacts from forestry activities are not allocated onto the wood consuming industries, forestry is the main contributor to urban land occupation- (ULO), natural land transformation- (NLT) and agricultural land occupation (ALO) impacts. However, by considering the total felling volumes and the respective wood industries' share of these in the given scenario, the respective industries' approximate share of the impacts caused by 'Norwegian forestry' could easily have been calculated as well.

4.3.3 Breakdown of environmental impacts in the alternative scenario

As in section 4.2.3, the distribution of impacts in the alternative scenario is presented relative to the total impacts in the reference scenario.

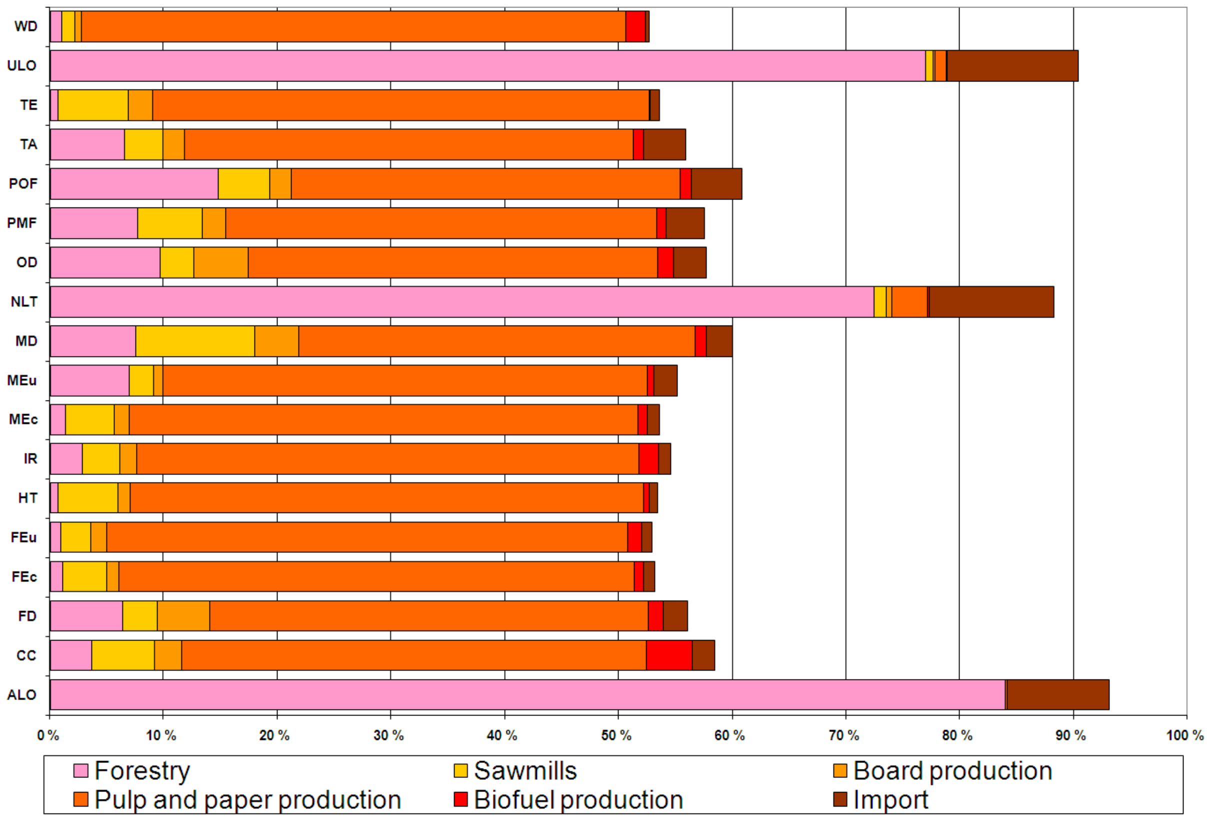

Figure 8: Breakdown of environmental impacts within the Norwegian wood products sector in the alternative scenario

Similar to the national level, the relative distribution has not changed much in the alternative scenario. Of course, pulp & paper production now constitute a smaller relative share of the total impacts than before, but due to this industry's dominance it is still by far the most important contributor to most environmental impacts.

4.4 Results at product level

The developed model can also be used to perform single product life cycle assessments. In this report, only LCA results for the domestic, wood-based end-products are presented, as the environmental impacts breakdown of these are of particular interest. However, for comparison purposes total impacts for some of the non-wood products are also presented in table 13.

For presentation purposes, climate change is the only impact category shown for the individual product LCAs. The impact category results are given per functional unit (FU), e.g. per tonnes, per sm^3, etc. Although table 13 and figure 9 only show results for the reference scenario, similar product assessments were carried out in the alternative scenario as well. Naturally, the only product categories who even had slightly different results in the alternative scenario were the ones who experienced a new wood input structure (i.e. pellets & briquettes, heat_WB_bio, heat_pellets&briquettes and bioethanol). However, since the results in the both cases were quite similar, i.e. only insignificant small differences, a separate presentation of the alternative results were considered unnecessary.

Table 13: The climate change (CC) impacts for some Norwegian wood products and their 'non-wood alternatives' in the reference scenario

Product	FU	Total CC (kg CO2-Eq/FU)	CC from biogenic (kg CO2-Eq/FU)
Sawn timber (not planed)	sm3	112,04	66,68
Planed timber	sm3	124,93	67,23
Fibre boards	sm3	546,80	121,94
Particle boards	sm3	307,72	50,66
Gypsum boards	tonnes	323,55	6,50
Paper and cardboard	tonnes	1386,51	443,99
Imported paper and cardboard	tonnes	1387,30	433,94
Pellets & briquettes	tonnes	112,73	7,31
Heat_WB_bio	MWh	199,08	160,70
Heat_logs	MWh	165,73	148,76
Heat_pellets	MWh	221,98	153,36
Heat_oil	MWh	311,17	0,13
Bioetahnol	GJ	50,25	36,08
Gasoline	GJ	84,40	0,02

The table above shows that climate change impacts caused by biogenic CO_2 and CH_4 emissions constitute a significant part of the total CC impacts for many of the wood based products. By for instance considering bioethanol, where approximately 72% of the total CC impacts result from biogenic emissions, it is obvious that this aspect have significant importance for the final results[18] and subsequent recommendations to decision makers. Although the results from this assessment still indicate a 40% reduction in CC impacts when substituting gasoline with bioethanol, the reduction would had been 83% if biogenic CO_2 and CH_4 had been considered climate neutral.

As previously mentioned, a gypsum board density of 0.6 tonnes/ sm^3 was applied in this assessment. An interesting observation is that when comparing one cubic meter of gypsum board to one cubic meter of particle- or fibre board, both wooden board types have higher CC impacts than gypsum boards. This is why the substitution of wooden boards had a direct positive effect on overall climate change impacts in the alternative scenario (see section 4.2.1).

[18] In the product LCA results shown in table 12 the use phase of bioethanol and gasoline is included

The results for the wood based heat categories indicate that heat from wood is most efficiently utilized, at least in terms of CC impacts, when the wood is combusted without having gone through several refining steps in advance. However, other aspects such as e.g. effective regulation of temperature, which is much easier for both waterborne heat and pellets/briquettes stoves than in traditional fire stoves, are not a part of the results presented here. The possibility for more effective utilization of the energy can in fact lead to a conclusion (without this having been investigated here) that heat from fire logs is the least attractive alternative of the three, even in terms of CC impacts. As in the case of transportation fuels, we see that biogenic CO_2 and CH_4 emissions have a significant impact on the relative CC performance of wood based heat categories compared to heat from oil.

It was shown earlier that the change in CC impacts from total paper production (i.e. foreign and domestic) was quite small. The reason for this can be seen in the table above where imported paper and cardboard only has a slightly higher CC impact than 'paper and cardboard' per tonne. As electricity is an important contributor to CC impacts, and the applied Norwegian electricity mix has a considerable lower CO_2 intensity than the European mix (used in foreign pulp- and paper production), due to its higher share of renewable energy, the calculated results may seem strange. The explanation probably lies within the complex modeling of the domestic pulp- and paper production process (see section 3.5.1). Due to the dominant position of the pulp & paper industry in this system, with respect to environmental impacts, the overall results (i.e. which scenario is best) proved highly sensitive to this part of the model. Therefore, the challenges associated with this will be further debated in the discussion (section 5.2.2).

Figure 9 illustrates the breakdown of the wood products' CC impacts onto various parts of the value chains. As before, the 'Import' category represents the impacts embodied in wood imports going into the Norwegian wood products sector as input materials. 'Other production processes' refer to the impacts caused by the remaining activities in the value chain, typically processes at e.g. sawmills, pulp- and paper plants, heat production plants, etc.

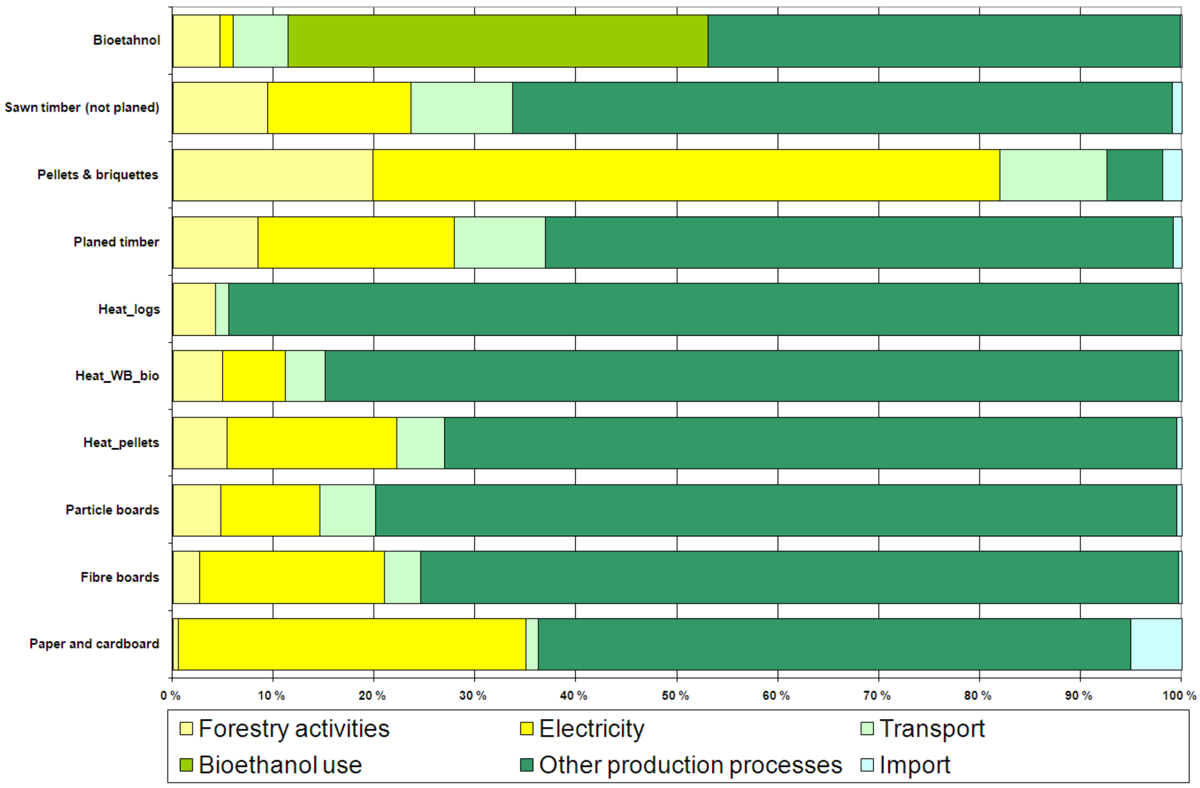

Figure 9: Breakdown of environmental impacts for some Norwegian wood products sector in the reference scenario

The figure above shows that electricity is a significant contributor to CC impacts for most of the products, especially for paper and pellets & briquettes. The impacts from forestry activities and transport, on the other hand, are relatively small for all products.

For bioethanol, timber, boards and paper, the CC impacts from 'Other production processes' are mainly due to the produced heat, either from wood and/or fossil sources, needed in the refining processes. For the different heat products, this breakdown category almost exclusively represents the CC impacts from combustion of the various fuels.

It is quite interesting to see that approximately 60% of the CC impacts resulting from the use of 1 GJ bioethanol originate from the production of the fuel, i.e. only 40% from the use phase. This shows that continued effort to increase the efficiency in production of liquid biofuels can help further improve the climate change mitigation effect of such fuels. As mentioned earlier in section 3.5.2, a thermochemical ('best case scenario') production process, as described by Bright et al. (2009a), was assumed in this model. In their assessment, Bright et al. found that the biochemical production process had even higher CC impacts in the production phase than the thermochemical alternative (approximately twice as big in the 'worst case scenario').

Consequently, there can be a significant difference in climate mitigation potential even between different types of wood-based transportation fuels.

5 DISCUSSION AND CONCLUSIONS

In this section, the assessment results, the developed model (including its strengths and weaknesses), assumptions made and potential contributions from this master thesis is discussed. Besides, some thoughts are suggested on how the model can be further improved in eventual continued work on this subject.

5.1 Results

5.1.1 Treatment of biogenic carbon emissions

The results from this work show that there are considerable reductions to gain in most environmental impact categories when performing a shift in utilization of the Norwegian wood resources towards more production of biofuels. However, the results also show that these reductions would have been much higher if biogenic CO_2 and CH_4 emissions were treated as climate neutral, as has been the most common approach in LCAs so far. This traditional approach can be a reasonable assumption for combustion of fast growing species (e.g. annual crops), but for a forest, which may take up to 100 years to re-grow, it is quite obvious that there will be a net climate impact as the carbon is emitted during a short period of time and the subsequent sequestration is spread out over several decades.

Another relevant aspect is the age of the biomass being harvested. The older the biomass is at the time of harvesting, i.e. the closer it is to decay and subsequent carbon emissions, the higher the climate mitigation effect of utilization for bioenergy purposes will be as the carbon would have been released soon anyway, although not as fast as under immediate combustion. Consequently, one should ideally only harvest old trees, and leave the younger ones behind to continue their sequestration of carbon. Unfortunately, such a practice is in many instances not economically viable as it implies time consuming classification of the trees and longer average transport distances within the forest.

An important conclusion from these results is that emissions of biogenic carbon dioxide and methane are of great significance to the climate change mitigation potential of wood-based bioenergy. In light of recent research, supported by the results in this work, previous environmental assessments of wood-based biofuels should probably be revised if they have treated biogenic carbon emissions as climate neutral. Otherwise, we risk investing much time and effort in climate mitigation measures that are less effective than other alternative measures. However, it is in this context necessary to distinguish between a short term perspective (e.g. the next 100 years) and a long term perspective. Although bioenergy might not be as effective as previously expected in combating the urgent climate change problem, it should be noted that in the long term, when atmospheric GHG concentrations are back to normal levels, bioenergy can surely be a sustainable source of energy. In other words, the need for further research and development within this industry is still very much relevant.

5.1.2 Environmental characteristics of the system

Not surprisingly, the results showed that the production of paper and heat, together with the production and use of transportation fuels, were in both scenarios the dominating contributors to most of the impact categories when applying the complete demand vectors. The total climate change impact for the overall system in the reference scenario was calculated to 14.1 million tonnes CO_2 equivalents, which e.g. corresponds to 26% of total GHG emissions (53.5 million tonnes CO_2 equivalents) in Norway in 2006 (Statistics Norway, 2011e).[19] For the alternative scenario the corresponding number was 13.8 million tonnes. In other words, the overall system is of considerable size in an environmental perspective.

When studying only the Norwegian wood products sector, the total CC impact was found to be 4.31 million tonnes CO_2 equivalents in the reference scenario and 2.52 million tonnes in the alternative scenario. The sector's environmental impacts are, in general, heavily dominated by the pulp & paper industry in both scenarios. This was also expected in advance, as this is a big industry with huge demands for electricity, heat, chemical and other inputs.

Considering the individual product assessments, the CC results for some of the products are probably considerably higher than in many other LCAs as this model uses a Norwegian electricity mix adjusted for trade with RECs (i.e. a more 'dirty' mix) and include CC impacts from biogenic carbon. For instance, although the methodological foundation behind the MIKADO project's environmental product declaration (EPD) for Norwegian sawn timber

[19] It should be rembered that the defined system also includes some foreign emissions

(Grini, 2009) is unknown, it can be assumed that the two aspects mentioned above are not considered in this EPD as it concludes with an CC impact of 19.1 kg CO_2-eq./sm^3 (Grini, 2009). In comparison, this assessment concludes with an CC impact of 112.04 CO_2-eq./sm^3, which is almost six times as high. However, we see that if had neglected biogenic carbon emissions (constituting ~60% of the total CC impacts), and used an el-mix (constituting ~15% of the total CC impacts) with minimal fossil energy, the results would have been quite close to the ones described in the EPD.

As the assessments were carried out, it became clear that, due to the pulp & paper industry's large share of the impacts in almost all impact categories, the results are very sensitive to differences in modeling of foreign and domestic pulp- and paper production process. This challenge is discussed in section 5.2.2.

Although this work does not consider the possibility to simply increase annual wood harvest levels, only a shift in current utilization, the results do tell something about the additional potential for reductions in environmental impacts when increasing the total forestry output as well. For instance, they show that substituting gasoline with wood-based bioethanol and fossil-based heat with wood-based heat reduce total CC impacts considerably. As mentioned introductorily, Norwegian forests currently experience a considerable annual net growth (15 million cubic metres in 2005). Alternatively, this increasing wood resource potential could be used for bioenergy purposes, without having to reduce production of other wood products. The challenge her lies in making more of the wood economically available for the bioenergy industry, i.e. making it profitable to harvest and process. This would require a larger marginal profit in the industry than what is the case today, e.g. as a result of higher energy prices or substitutes.

Another option is to increase the utilization rate of forestry residues (i.e. branches and tops (BRAT)). This resource emerges as a direct consequence of the felling of threes, and unless it is utilized it will remain in the forest where it will eventually decay. Consequently, as well as being a relatively cheap resource (Nordland et al., 2003, p.8), using BRAT for bioenergy purposes can be considered to be very 'climate effective'. The trade-off here lies in balancing the need for a cheap and climate friendly energy source with the need for biodiversity and supply of nutrients to the forest soil.

5.1.3 Consequences of using a 'global perspective'

Since climate change impacts, as well as many other environmental issues, have global effects, it was necessary in this work to ensure that additional impacts occuring outside Norway as a result of changes made to the Norwegian system were captured by the model. Otherwise, conclusions made on which scenario is better and which substitutions are most effective could easily have been discredited by pointing to the neglected, resulting foreign impacts.

However, the developed model is still unable to cover some other important aspects. First of all, the model does not consider the fact that when less electricity is consumed in Norway (e.g. due to reduced paper production) the same amount of environmentally friendly hydro power can replace more dirty energy sources in applications outside the defined system. Since many renewable energy sources such as e.g. hydro-, wind-, wave-, tidal- and solar power are resources that are lost if not utilized whenever possible (unlike fossil resources), it is natural to assume that the Norwegian hydro power production would remain pretty constant regardless of this system's demand for Norwegian electricity. Consequently, this is an argument that further supports the environmental benefits from a shift towards the defined alternative scenario.

Correspondingly, the model does not consider that, when assuming fixed demand levels for wood products and a fixed global wood resource base, more use of wood for bioenergy purposes in Norway would imply less wood available for such purposes in the rest of the world. Unlike the electricity aspect, this argument undermines the defined alternative scenario.

Developing a model that included such relationships would eventually require an inclusion of all industries (in all economies) as well as all product categories. Understandably, this would require an enormous amount of work if a reasonable level of detail was to be maintained, and therefore not considered possible within the limited time frame of this work.

5.2 Assessment of applied data and assumptions

5.2.1 Wood flow mapping

As previously mentioned, the data collection process regarding the flow mapping proved much more difficult than initially expected. Even though much data exists on e.g. annual felling quantities and final production of end products, there is a considerable lack of available data on the intermediate flows within the wood related industries. This observation has given further confidence to the impression that having established an overview of these flows will generate some value added to work dealing with environmental assessments of Norwegian biofuels and other wood related products. Some of the reasons for why this data collection process has been so challenging can be identified:

- ✓ Most available data has a high aggregation level, i.e. low level of detail
- ✓ Lack of available data on some important categories, especially for intermediate flows but also for some primary production (e.g. annual felling of energywood and forestry residues)
- ✓ Variations in use of product categories, and product category nomenclature, between the different sources
- ✓ Variations in use of units (e.g. sm^3, tonnes, MWh and joules) and the subsequent need for general conversion factors (e.g. average density for pellets and briquettes)
- ✓ Contradictions between some data sources
- ✓ The need to balance the flows, in order to assure that the Make & Use tables are applicable to the IOA framework.

In order to solve these issues some rough estimations and assumptions were necessary. Data collection in environmental system analysis is always a trade-off between effort and expected significance of having slightly more accurate data. The author's opinion is that the flow data in general is of quite high credibility. Although they flows might not be exact in all cases, they seem to be in the right range as several sources have been compared in many instances. Given the fact that an environmental assessment never will be 100% correct, due to the large amount of parameters and uncertainties (both in the inventories and the impact assessment methods), approximately accurate flows can be considered good enough. One should also remember that the data collected in this work is from 2006, and that the actual figures vary somewhat from year to year. Consequently, the expected value of spending even more time on mapping these flows was evaluated to be quite small as the figures will have changed to some degree anyway by now. To sum up, the derived Make & Use tables should not be considered as exact overviews, but rather as useful tools in developing life cycle inventories that are more representative to the Norwegian wood industries than the ones found in standard LCA databases.

5.2.2 Process datasets

Almost all of the process data in this model is taken from the Ecoinvent v2.2 database (2010). The datasets found there are well documented in scientific reports and utilized by more than 2500 users in more than 40 countries worldwide (Swiss Centre for Life Cycle Inventories, 2010). The Ecoinvent data is widely acknowledged to be of high quality and since establishing such inventories can be extremely time consuming one should have considerable reasons to believe that the existing datasets are unsuited for a specific purpose before building entirely new inventories (i.e. collecting project specific data). Industries and technologies are constantly evolving and in order to be able to justify having updated process data, i.e. have the resources to make iterative changes, there is a need for a huge user volume. In other words, collecting Norwegian specific data on a vast amount of industrial processes is probably not justified. However, modifications to key aspects of the Ecoinvent datasets can (and should) be made whenever it is possible to make the datasets more representative to the actual situation. This requires that credible alternative data is available and that the LCA practitioner is consistent in the data modification process so that a fair comparison between the different processes is maintained.

As described in section 4.2.1 and 4.4, the results from this work indicated an insignificant difference in climate change impacts from foreign- and domestic pulp & paper production. This is somewhat strange given that the developed model, although in principle assuming equal technology for both cases, applied a different electricity mix and wood input structure for domestic production. Given the high share of renewable energy in the Norwegian electricity consumption mix (see section 3.5.1), in combination with electricity's significance to CC impacts, it could have been expected that the impact results for domestic pulp & paper production should be considerable lower than foreign production. It is very likely that the problem lies within the complex modeling of the domestic pulp & paper production (described in section 3.5.1). Due to the pulp & paper industry's significance in the studied system, this is also probably is the greatest weakness of the developed model.

The main challenge here is to determine whether one should have a low aggregation level (i.e. many different pulp and paper products), which involves complex modeling and subsequent risk of unfair comparisons between foreign and domestic production, or if one should assume equal technology for all pulp- and paper products respectively. The latter would on the other hand severely comprise the level of detail as the different production processes within this industry are known to have quite different requirements for e.g. heat, electricity and chemicals. Another option is of course to collect country specific data from various Norwegian pulp and paper producers, which would be very time consuming, and then build Norwegian life cycle inventories for a vast amount of pulp and paper products. However, there would still be a significant risk that comparisons based on this approach would be unfair, unless one is absolute sure that the same assumptions made in the Ecoinvent datasets are applied.

The modeled Norwegian electricity described earlier (see section 3.5.1) includes the trade of renewable energy certificates (RECs). As Norway has a considerable net export of such certificates, the modeled mix contains a significant higher share of non-renewable energy than the Norwegian production mix. This is a necessary step considering the very intention of the renewable energy certificate system (RECS), which is to stimulate increased production of renewable energy by issuing the producers a certificate per MWh produced which then can be sold on the certificate market, increasing the profitability of renewable energy production. The idea is that consumers and businesses looking to improve their environmental profile, can buy the certificates in order to claim that their power consumption comes from renewable sources. When these certificates are sold to buyers outside of Norway, domestic consumers should not be able to claim the same imaginary electric flow, although the physical flow is the same. If so, it would lead to a situation where both parties claimed to use the same MWh of renewable energy, which in turn would reduce the demand for such certificates.

As a consequence, all environmental assessments should in principle apply electricity mixes adjusted for RECs trade whenever it drastically changes the environmental profile of the mix. It was also assumed in this assessment that none of the domestic industries in the model buy renewable energy certificates. This is a valid assumption as the dominating perception in most Norwegian businesses is that the electricity they use is almost exclusively renewable hydro power anyway.

To sum up, the applied model is mainly based on Ecoinvent datasets who are generally considered to be life cycle inventories of very high standard. Additionally, Norwegian specific sources were used to double-check the data found in Ecoinvent wherever such information was available. With the exception of the pulp & paper industry, the author's impression is that the model is of overall good quality.

5.2.3 Alternative scenario modeling

When evaluating different strategies for how we best can utilize the resource potential in our forests there are of course several other aspects than environmental concerns that should be considered. Economics is perhaps the most important factor for most decision makers (e.g. politicians), and a different utilization of a Norwegian wood (e.g. towards more bioenergy) would have to be economically viable in order to sustain over time. Furthermore, there are many different considerations that must be taken when evaluating which wood flows that can be changed without creating some sort of problem. For instance, one would have to evaluate which products that can replace other products while maintaining the same functional properties, i.e. ensure that they have the same area of application. Another thing to consider is already available infrastructure. This can be exemplified with the pulp and paper industry, which is characterized by high capital costs (Bolkesjø, 2004, p.15). When a pulp (or paper) plant already is built it would most often be optimal to produce at full capacity. In other words, reducing domestic production in this industry may be considered unrealistic in the short term as long as the current infrastructure is operational.

Consequently, establishing highly realistic alternative scenarios involves a considerable amount of work as many different aspects must be studied in detail. Given the limited time frame of this assessment, the alternative scenario described here is most likely primarily suited for illustrative purposes, i.e. to show the possibilities embedded in the applied model and framework when performing scenario life cycle assessments. Before making well-founded conclusions on how Norwegian wood should be utilized in terms of overall environmental impacts, more work should be put into developing more realistic scenarios than the one developed here. Furthermore, only one scenario is in itself not enough to decide the optimal utilization, as this is just one of many possible scenarios.

5.3 Final conclusions and suggestions for further work

Due to large amount of result data, many conclusions could be made from this work regarding various environmental gains resulting from a shift in utilization of Norwegian wood resources. However, due to the previously mentioned inadequacies in the modeling of the alternative scenario and in the pulp- and paper production processes, the author's impression is that the developed model first of all is suited to provide a rough, general impression of the system's/products' environmental characteristics, useful for further assessments within this field.

Other important contributions from this work are:

- ✓ The flow mapping in itself, primarily as a tool in developing environmental LCIs more representative to Norwegian conditions, but also applicable to other purposes (e.g. economic equilibrium models)
- ✓ A hybrid-LCA model of the Norwegian wood products sector with the ability to both assess 'the bigger picture as well as zooming in on specific industries and/or products

Furthermore, the assessment results show that the climate mitigation effect of increasing the share of bioenergy is heavily dependent on whether or not biogenic CO_2 and CH_4 emissions are considered to be climate neutral. This conclusion supports the need for further research on this field. Until now, bioenergy has been considered climate neutral and therefore been an important part of many countries' (including Norway) strategy to combat climate change. A change in this perception could drastically re-write the political agenda towards low-carbon economies.

It can also be mentioned that when neglecting biogenic carbon emissions, the results in terms of difference in total climate change impacts between the scenarios, quickly becomes much less sensitive to the different assumptions (e.g. Norwegian electricity mix, Norwegian pulp- and paper modeling, etc) made in the model. In other words, then the alternative scenario is so much better than the reference scenario that the assumptions become less important to the final conclusion of which scenario is better. However, neglecting this aspect is, as previously explained, not recommend. To conclude, the results in this assessment tell something about the particular need for accurate modeling in this system when making conclusions on how Norwegian wood should be utilized.

In further work, it is suggested that much emphasis is put on:

- ✓ Developing well-founded scenarios for wood utilization where aspects such as e.g. economic and social issues, already available infrastructure and substitution challenges (e.g. which wood products can be replaced by alternative product without compromising the area of application) are considered
- ✓ Accurate, consistent and transparent modeling of the pulp- and paper production processes in order to ensure a fair comparison of foreign and domestic paper

Although this thesis provides some useful insights, much more work is needed in order to be able to make final conclusions on an optimal utilization of Norwegian wood. Still, hopefully this work can provide one of many starting points for further assessments, both environmental and other, within the field.

6 ACKNOWLEDGMENTS

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APPENDIX A

MATLAB-file:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CenBio-Wood based products in Norway: Scenario LCA
%
% by
% Magnus Grinde, MSc Energy & Environment, Department of Energy and
% Process Engineering, NTNU
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
filename = 'M&U Norwegian Wood Industry_REVISED.xls';

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Loading and preparing data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Reading the M and U matrices
M = xlsread(filename, 'Derivations_overview', 'D4:S51');
U = xlsread(filename, 'Derivations_overview', 'D57:S104');

% Reading the NFD vector
Y = xlsread(filename, 'Derivations_overview', 'X4:X51');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculation of product output (q) and industry output (g)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

m = size(M,1);  %number of products
n = size(M,2);  %number of industries

i = ones(n,1);  %vector of only 1's
j = ones(m,1);  %vector of only 1's

q = M*i;
```

```
g = (M')*j;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculation of Use Coefficient-(B), Market Share-(G)and Product Mix (H)
% matrices
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

B = U*diag(g)^-1;
G = (M')*diag(q)^-1;
H = M*diag(g)^-1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% An A industry by industry matrix using industry technology assumption
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A_IT_nn = G*B;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% An A product by product matrix using industry technology assumption
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A_IT_mm = B*G;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Constructing I matrices, used in derivation of L-matrices
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

i_nn = ones(n,1);
I_nn = diag(i_nn);

i_mm = ones(m,1);
I_mm = diag(i_mm);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% An L industry by industry matrix using industry technology assumption
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

L_IT_nn =(I_nn-A_IT_nn)^-1;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% An L product by product matrix using industry technology assumption
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

L_IT_mm = (I_mm-A_IT_mm)^-1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The primal (material) balance
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Y_ind = G*Y;        %Net final demand for industries (industry tech.
assum.)

x_n = L_IT_nn * Y_ind;
x_m = L_IT_mm * Y;
```