Life cycle assessment of mountain forest wood fuel supply chains: case studies from Norway and Italy

Bioenergi fra fjellskog: livsløpsanalyser av verdikjeder. Casestudier fra Norge og Italia

Clara Valente

Norwegian University of Life Sciences • Universitetet for miljø- og biovitenskap
Department of Ecology and Natural Resource Management
Philosophiae Doctor (PhD) Thesis 2011:57

Life cycle assessment of mountain forest wood fuel supply chains: case studies from Norway and Italy

Bioenergi fra fjellskog: livsløpsanalyser av verdikjeder. Casestudier fra Norge og Italia

Philosophiae Doctor (PhD) Thesis

Clara Valente

Department of Ecology and Natural Resource Management (INA)

Norwegian University of Life Sciences

Ås 2011

Thesis number: 2011:57

ISBN-nr.: 978-82-575-1020-6

ISSN-nr.: 1503-1667

Supervisors

Prof. Dr. Birger Solberg
Department of Ecology and Natural Resource Management (INA)
Norwegian University of Life Sciences

Prof. Dr. Bengt Gunnar Hillring
Faculty of Applied Ecology and Agricultural Sciences
Hedmark University College, Norway

Senior Res. Dr. Raffaele Spinelli
CNR IVALSA- National Research Council- Timber Technology Institute, Italy

Prof. Dr. Ståle Navrud
Department of Economics and Resource Management
Norwegian University of Life Sciences

PREFACE

This thesis is a partial fulfilment of the requirements for the PhD degree at Department of Ecology and Natural resource Management (INA), Norwegian University of Life Sciences. Hedmark University College, Faculty of Applied Ecology and Agricultural Sciences financed the PhD study.

I would like to thank Hedmark University College, campus Evenstad for funding the study, but also for making real my wish to do a PhD in a Nordic country.

I am grateful to all my supervisors: Bengt Gunnar Hillring, Raffaele Spinelli, Birger Solberg and Ståle Navrud for their scientific guidance and encouragement. Bengt was the motivation for this project. He was always open to discuss science, but also he explained Scandinavia culture to me. Raffaele brought me into the Italian forestry sector (grazie). Birger and Ståle accepted me as a PhD student at Norwegian University of Life Sciences.

I would like to thank all of you because of the freedom and trust in my work and the possibility to travel in Scandinavian countries for conferences, courses and data collection. It was helpful for increasing my skills in communication, sharing knowledge, receiving scientific inputs, but also for learning another way of thinking and living.

Thank you Jos for English revision of my work and Hanne for the Norwegian translation of both abstract and title.

I am grateful to my colleagues and friends at Hedmark University College and INA for their assistance and sharing time with me.

Thank you and thank you again to all my friends from Ås, they are so many that I do not have enough space for listing your name, but you know whom I mean. You filled up so many moments in these three years and we spent so much time together and had fun, that the *little carrot* will remember it for all her life.

Thank you to my Italian friends, wherever you were.

Last, I would like to say grazie and dedicate this thesis to my parents and my brother who have supported me in this adventure despite the distance. I missed you so much.

In conclusion for all PhD students and readers: "nothing is impossible until it is done". Three years ago, I moved to Norway and I looked at the end of the PhD as something so far and unachievable. Now this moment is here.

Evenstad and Ås, September 2011.

Clara Valente

SUMMARY

Concerns about the fast growth in greenhouse gas emissions have encouraged several countries to increase their use of renewable energy. According to the EU's Renewable Energy Directive (RED), 20% of all the energy production in the EU should come from renewable energy sources by 2020. Woody biomass can be one choice within bioenergy for mitigating climate change if replacing fossil fuels. However, the demand for wood fuels has increased recently, and in Europe, the demand is predicted to exceed European supply, so we therefore need to consider more wood energy sources. Here, wood fuels from mountain forests can be an interesting alternative. Globally, mountain forests cover 28% of the total forested areas, while in Europe one quarter of the forest is located in mountain areas. Thus, there is a large potential for harvesting woody biomass for bioenergy use.

The aim of this PhD study is to assess the GHG emissions associated with two wood fuel supply chains from mountain forests. Two case studies, one in Norway (Hedmark-Oppland counties) and one in Italy (Valle di Fiemme -Trentino-Alto Adige region) are analyzed and compared. The methodology used is the Life Cycle Assessment, which is an established tool for assessing the mentioned environmental impact for the supply system through its life cycle – from the forest stand to the user (bioenergy plant), through forest management, logging operations, transportation and combustion at the plant. The chosen functional unit is one solid cubic meter over bark (1 m^3 s.o.b.). The environmental impact category under assessment was climate change, expressed as global warming potential (GWP) with a time horizon of 100 years in terms of the amount of GHG emissions. In the study, a cost analysis (NOK or euro/m^3 s.o.b.) is performed, and an analysis of the employment impacts (hours/m^3 s.o.b.) is conducted in the Italian case related to the examined supply chains. Comparison with lowland forest or other types of renewable energy is outside the scope of this study. The PhD thesis consists of four papers. Papers 1 and 2 deal with the Norwegian case study, while Paper 3 describes the Italian case study. Paper 4 compares the main findings of each case study, analysing the differences and similarities between the Norwegian and Italian supply chains.

Paper 1 provides the first part of the Norwegian case study, comprising the production stages from the mountain forest stands to the terminal. Mountain forests were highlands located in flat terrain. Forest management, logging operations and transportation to the terminal were the processes assessed. Forest residues, generally left at the forest stand, were harvested and

bundled. Fuel consumption, raw material and primary energy use were calculated as input parameters. Results showed that the operation with the highest emissions and costs was transportation of woody biomass to the terminal, due to high fuel consumption and long transportation distance. Forest management had the lowest emissions, but highest costs. Bundling had high emissions and costs, even if long transport distance might make this operation advantageous in mountain areas. The present forest management and transport logistics are elements, which can be improved, seen from a GHG perspective.

In Paper 2, the second part of the Norwegian supply chain is assessed; i.e. from the terminal to the biomass combustion plant. The benefits of replacing fossil fuel (natural gas, coal and oil) with wood fuel from the mountain sites, as described in paper 1, were calculated based on the assumption of carbon neutrality. Two alternatives were analyzed: i) a local supply chain, where raw materials from lowland forests were chipped at the terminal and transported by truck to a local district heating plant, and ii) an international supply chain, where raw materials from both lowland and highland forests were chipped at the terminal and exported by train to a combined heat and power plant in Sweden. The local supply chain had larger emissions than the export alternative. Both railway transportation and energy cogeneration made the international supply chain more efficient than the local alternative. The wood chips from mountain forests in Norway can be an option for covering the increasing demand for wood fuels in Sweden. Furthermore, the results indicate that the export of wood chips from Norway to Sweden is currently economically viable.

Paper 3 presents the Italian case study carried out in Valle di Fiemme-Trentino region. In this paper, the social aspect (i.e. the direct employment potential) was assessed in addition to the environmental and economic aspects. The LCA concerned a local supply chain from mountain forest stands located in steep terrains to combustion at a district heating plant, where wood fuels were assumed to replace a fossil fuel plant (natural gas or oil plant). Logging residues, generally left at the forest stand, were harvested and chipped at the landing site. Chipping was the operation with the largest emissions followed by transportation by truck. Extraction by cable yarder was the operation with the highest costs along the supply chain. Regarding the analysis of employment, transportation and yarding operation created working opportunities. The use of woody biomass for energy can generate new jobs, although the topic of job creation is under discussion in the forestry sector. Furthermore, comparisons between an innovative (more mechanized) and a traditional logging system (more manual work) were presented, indicating that the substitution of a motor manual with a mechanized logging system reduced both emissions and costs.

Paper 4 compares results from the Norwegian case study (paper 1 and 2) and the Italian case study (paper 3). Distinctive features of each case study, both similarities and differences, are discussed. The main results from the Norwegian case study were: a high rate of mechanization in harvesting highland forests located in flat terrain, chipping at the terminal, and a preference for an international supply chain (i.e. export to Sweden). The main features of the Italian supply chain were: a predominance of motor manual operations, felling trees in steep terrain, chipping at the landing of logging residues, absence of a terminal, and a local supply chain. The overall comparison between the case studies showed larger emissions for the Norwegian supply chain than the Italian one, due to higher mechanization and more steps involved in the supply chain. That also explained the higher costs for the Norwegian case. However, the greenhouse gas balance for the studied supply chains was still positive when wood fuels substituted fossil fuels. The analysis of employment was a critical aspect, and needs further investigation.

The papers show large differences in how wood fuel supply chains are handled in the studied mountainous areas, making it difficult to formulate general conclusions. However, our case studies clearly show the potential for using woody biomass for bioenergy from mountain forests and the feasibility of harvesting wood fuels there with positive GHG impacts and without increasing the operative costs dramatically. The improvement of critical aspects of the supply chain operations may reduce emissions and costs. The evaluation of other impacts, in particular biodiversity aspects and deeper analyses should be made to ensure the fulfilment of sustainability criteria.

SAMMENDRAG

Bekymringer vedrørende den store økningen i klimagassutslipp har ført til en sterk interesse i bruk av fornybar energi, herunder bioenergi. Bioenergi fra skog har store muligheter til å redusere klimagassutslippene når fossil energi erstattes. Den økte etterspørselen etter bioenergi fra skog har gjort at flere land har begynt å se etter alternative kilder for slik energi. Bioenergi fra fjellskog har vist seg å være en interessant mulighet. Målet med denne doktorgraden er å vurdere klimagassutslippene fra to tilbudskjeder for bioenergi fra fjellskog. To casestudier, en i Norge (Hedmark og Oppland fylker) og en i Italia (Valle di Fiemme - Trentino-Alto Adige-regionen) er analysert og sammenlignet. Livsløpsanalyse, en etablert metode for å studere miljøpåvirkninger av et produkt gjennom dets livsløp – i dette tilfellet bioenergi fra bestandet til bruker (bioenergianlegg) – er benyttet. Den funksjonelle enheten er en fastkubikkmeter over bark. Studien inneholder også kostnadsanalyser, og den italienske studien også en sysselsettingsanalyse.

Avhandlingen inneholder fire artikler. Artikkel 1 og 2 analyser den norske tilbudskjeden, mens den italienske studien er presentert i Artikkel 3. Artikkel 4 fremstiller hovedresultatene fra hver studie og sammenligner resultatene og konklusjonene for å belyse forskjeller og likheter mellom den norske og den italienske tilbudskjeden.

Den norske tilbudskjeden i studien kjennetegnes av en høy mekaniseringsgrad i avvirkningen, lokalisering av tømmeravvirkning i relativt flatt terreng, flising ved terminal og at den er internasjonal (eksport til Sverige). Den italienske tilbudskjeden karakteriseres av en overveiende bruk av motormanuelle drifter, avvirkning i bratt terreng, flising ved landing av hogstavfall, ingen terminal og lokal bruker. Den overordnete sammenligningen av studiene viser at den norske tilbudskjeden har en høyere mekaniseringsgrad og inkluderer flere driftsledd enn den italienske, noe som kan forklare de høyere klimagassutslippene i den norske kjeden. Reduksjonene i klimagassutslipp i energianlegget, altså unngåtte klimagassutslipp ved erstatning av fossile brennstoff med bioenergi fra fjellskog, var signifikante i begge tilfeller. Imidlertid bør man være forsiktig med å generalisere resultatene til andre fjellskogsområder. Videre foreslår vi at før økt avvirkning i de to områdene anbefales, inkluderes andre bærekraftskriterier i analysene.

RIASSUNTO

La preoccupazione per l'incremento delle emissioni di gas serra ha aumentato l'interesse per le fonti di energia rinnovabili tra cui la bioenergia. L'energia prodotta da biomassa legnosa diminuisce le emissioni grazie alla sua sostituzione con i combustibili fossili. La crescente domanda per i combustibili legnosi sta spingendo molti paesi alla ricerca di nuovi siti per l'approvvigionamento della biomassa legnosa, come le foreste di montagna. Lo scopo della tesi di dottorato è il calcolo delle emissioni di gas serra di due filiere, dove i combustibili legnosi provengono da foreste di montagna. Due casi studio, il primo in Norvegia (contee di Hedmark e Oppland) ed il secondo in Italia (Valle di Fiemme, regione Trentino-Alto Adige) sono analizzati e paragonati. La metodologia usata è la valutazione del ciclo di vita (LCA o Life Cycle Assessment), un metodo per valutare gli impatti ambientali di un prodotto attraverso il suo ciclo di vita -in questo caso il ciclo di vita del combustibile legnoso dalle foreste montane al consumatore finale (impianto a bioenergia). L'unità funzionale utilizzata è un metro cubo solido sopra corteccia. Lo studio include un'analisi dei costi e nel solo caso italiano anche un'analisi del lavoro.

La tesi di dottorato è formata da quattro articoli. Gli articoli 1 e 2 trattano il caso studio norvegese, mentre l'articolo 3 si occupa del case studio italiano. L'articolo 4 presenta le scoperte principali relative ad ogni caso studio, paragona i risultati e le conclusioni per identificare le differenze e le similitudini tra la filiera norvegese ed italiana.

Le principali caratteristiche del caso studio norvegese sono: alto tasso di meccanizzazione, taglio delle foreste montane che si trovano sugli altopiani, cippatura al terminal, e preferenza per una filiera internazionale (esportazione in Svezia). Le principali particolarità del caso studio italiano sono: predominanza delle operazioni forestali manuali, tagli in terreni pendenti, cippatura all'imposto dei residui forestali, assenza del terminal, e consumo locale. Il paragone tra i casi studio indica che la filiera norvegese, con maggiore meccanizzazione e più attività forestali coinvolte nella filiera, emette più gas serra della filiera italiana. I fattori sopra citati spiegano anche il perchè dei costi operativi più elevati. Le emissioni di gas serra evitate grazie alla sostituzione di centrali energetiche alimentate da combustibili fossili con centrali a biomassa legnosa proveniente da aree montane sono significative. Tuttavia, bisogna essere cauti nel generalizzare ed utilizzare i risultati ottenuti dai casi studio per altre filiere montane. Inoltre, si suggerisce di studiare altri criteri di sostenibilità e di svolgere analisi più approfondite, prima di consigliare lo sfruttamento più intensivo delle foreste di montagna per la produzione di bioenergia.

PAPER 1-4

Paper 1: Valente, C., Hillring, B.G., Solberg, B., 2011. Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. *Scandinavian Journal of Forest Research,* 26(5): 429-436

Paper 2: Valente, C., Hillring, B.G., Solberg, B., 2011. Greenhouse Gas Emissions, Energy Use and Costs of Wood Fuel Supply Chains in Scandinavia. *Submitted to Journal of Forest Energy*. (In review)

Paper 3: Valente, C., Spinelli, R., Hillring, B.G., 2011. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). *Journal of Cleaner Production,* 19(17-18): 1931-1938

Paper 4: Valente, C., Spinelli, R., Hillring, B.G., 2011. Mountain forests wood fuel supply chains: comparative studies between Norway and Italy. *Manuscript*

GLOSSARY

Acronyms and abbreviations

CHP plant: combined heat and power plant

DHP: district heating plant

GHG emissions: greenhouse gas emissions

GWP: Global Warming Potential

IPCC: Intergovernmental Panel on Climate Change

$kgCO_{2e}$: kilogram of carbon dioxide equivalent

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

MFWFSC: mountain forest wood fuel supply chain

s.o.b.: solid over bark

SWS: short wood system

WTS: whole tree system

Definitions used in the thesis

Bundling: production of compact residue logs (CRLs) or bundles (solid biofuels, which has been bound together and where there is a lengthwise orientation of the material). In case study A, logging residues are bundled through a slash bundler mounted on the forwarder (case study A);

Chipping: transformation of wood into wood chips, chipped woody biomass in the form of pieces with a defined particle size produced by mechanized treatment with sharp tools such as knives;

Combined heat and power plant (CHP plant): central combustion unit, where heat and electricity are generated simultaneously. In the thesis, wood chips are combusted for both internal use and district heating network;

District heating plant (DHP): central combustion unit, a network of heat distributed by pipes; in the thesis, wood chips are burned for producing heat to distribute to residential households (case study A and B);

Forest fuel: wood fuel produced where the raw material has not previously had another use;

Forest management: activities aimed at fulfilling specific human needs through forest utilization. In the thesis, the term forest management means: i) silvicultural system of *selective cutting*, defined as extraction of only part of the standing volume, for keeping uneven age forests; ii) *soil scarification*, removal of the top litter layer in the soil for improving the regeneration of the forest stands by a scarifier mounted on a conventional forwarder (case study A), and iii) *regeneration* or renewal of the forest stand artificially (planting: manual planting of seedlings cultivated in a tree nursery) –case study A or naturally (natural regeneration: leaving of some trees in the forest stand to provide seeds) -case study B;

Greenhouse gas (GHG): Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation within the spectrum of thermal infrared radiation. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Only CO_2, N_2O and CH4 are considered in the thesis.

Global Warming Potential (GWP): radioactive forcing change of GHG into the air (CO_2, N_2O and CH_4 in case study A and B) for a time period of 100 years (time horizon), used for calculating carbon dioxide emissions equivalent ($kgCO_{2e}$);

Harvesting: final felling of trees though a single-grip harvester (case study A) and chainsaw (case study B);

Logging residues: woody biomass residues, created during timber harvesting. In the thesis, above-ground biomass only, including branches and tops of the trees, is considered;

Mountain Forest Wood Fuel Supply Chain (MFWFSC): network of operations involved from the mountain forest stand to the user;

Processing: delimbing, bucking and stacking of trees through an excavator mounted processor (case study B);

Short Wood System (SWS): felling, delimbing and bucking trees into logs of specified lengths at the stump, by harvester and chainsaw respectively in case study A and B. Logging residues are left at the stand;

Terrain transport: removal of trees after harvesting and transport to the landing through a conventional forwarder (case study A) and cable yarder (case study B);

Transportation to the terminal: transportation of raw materials from the landing to the terminal, i.e., site for controlling the procurement process (case study A);

Whole Tree System (WTS): felling by chainsaw and extracting the whole tree by cable yarder, delimbing, bucking and stacking at the landing, where also logging residues are harvested;

Woody biomass: biomass originated by trees, bushes and shrubs. In the thesis only trees are considered;

Wood fuel: all type of biofuels (fuel produced by biomass) originated directly or indirectly from woody biomass.

The above definitions are based on the following literature sources:

Andersson et al. (2002), CEN (2004), Hakkila (2004), IPCC (2007), Lexerød and Eid (2006), Smith and Wigley (2000).

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

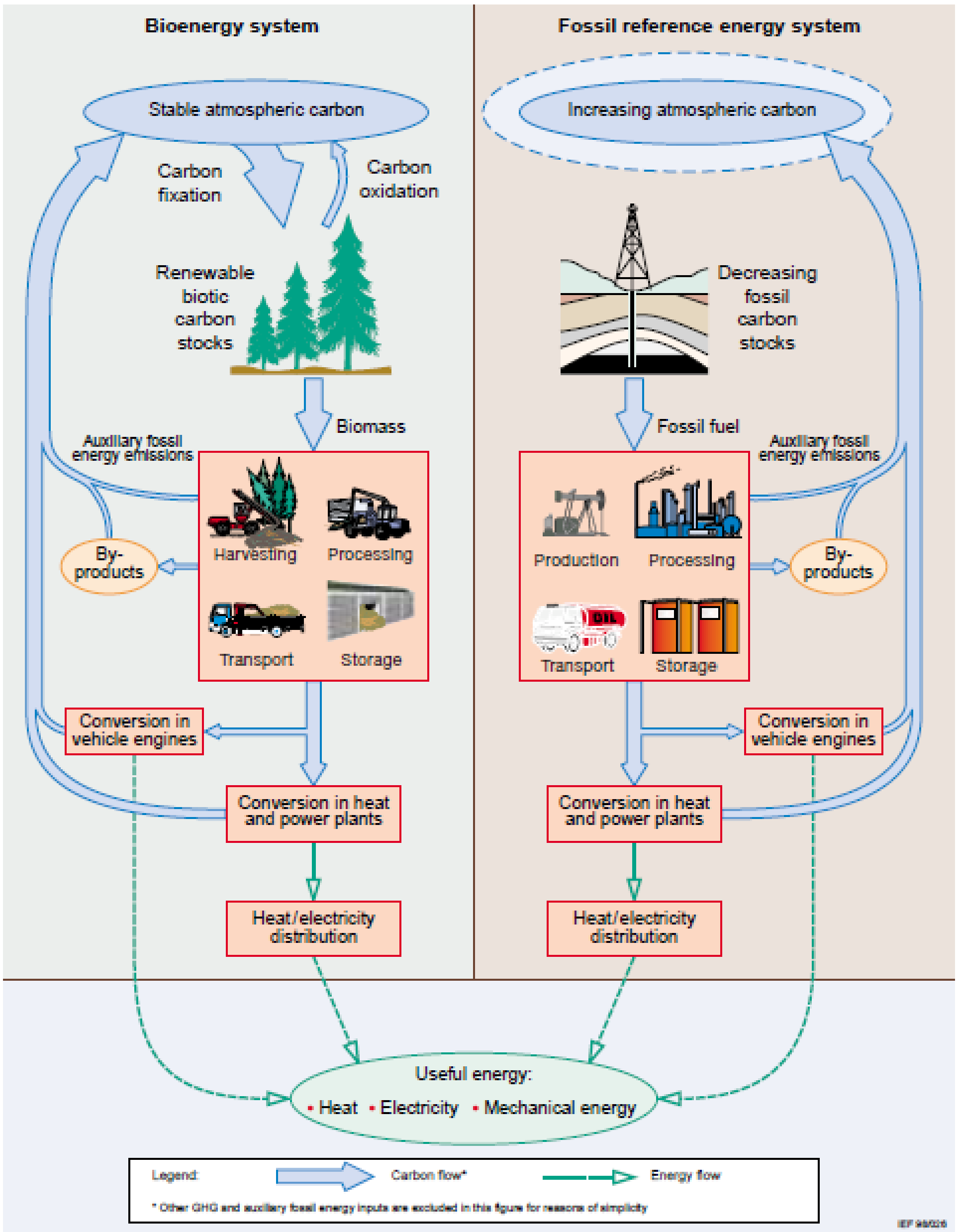
1.1 General introduction

The concern for climate change and the increase of greenhouse gas (GHG) emissions are becoming increasingly more important and debated issue. According to Intergovernmental Panel on Climate Change (IPCC) (McCarthy et al., 2001), human activities, in particular fossil fuel combustion and deforestation, are the main factors responsible for the increment in GHG emissions, where one possible strategy of GHG reduction is to replace fossil fuels with bioenergy. The assumption is that fossil fuels are net contributors of CO_2 emissions, contrary to bioenergy where CO_2 circulates in a biological system, maintaining stable levels in the atmosphere. This concept is more complicated in reality. Both fossil fuels and bioenergy emit CO_2 in the combustion process. Millions of years ago, geological formation captured fossil fuels, while current biomass circulates the CO_2 in the living plants and emits the same amount of CO_2 during decomposition as captured during growth. Some fossil fuels emit less GHG per energy unit than bioenergy. Hence, in a short period (10-20 years) natural gas, e.g., can be preferable to bioenergy (Holmgren and Olsson, 2008). However, in the long term, bioenergy is always favourable when produced in a sustainable way, i.e. harvest does not exceed growth and soil is kept properly. A forest system managed in a sustainable manner therefore has a great potential for climate change mitigation.

Several efforts have been made for reducing GHG emissions at the international level, such as the Kyoto Protocol (UN, 1998) and at the European level. Indeed, EU has adopted an energy policy based on a low carbon profile through the achievement of three targets: the reduction of GHG emissions by 20% compared to 1990 levels, an increment in the use of renewable energy of up to 20% of the total European energy consumption and the reduction of energy consumption by 20% (EU, 2009). Bioenergy is one possible choice between renewable energies for reducing GHG emissions, diversifying energy supply and limiting pressure on finished resources (IEA, 2007). Within the variety of bioenergy sources, woody biomass from forestry is an interesting energy source that already supplies energy in many parts of the world (Parikka, 2004). Woody biomass is available and exploitable now and in the next decades (Smeets and Faaij, 2007).

Continuous carbon circulation between forests and the atmosphere is assured by forest growth, deviating substantially from the fossil fuel system, as shown in figure 1. As described by Cherubini et al. (2009), in both system we should take into account GHG emissions and energy input originated by the production process of heat and electricity (harvesting-producing, processing, transporting and storage). Woody biomass can be a good option for energy production and can mitigate global warming due to its low emissions of GHG compared to oil and coal power plant (Sasaki et al., 2009; Sathre and Gustavsson, 2009).

Figure 1: Difference in the carbon circulation between bioenergy and fossil fuel systems. Source: IEA (2002)



For reaching international, European and national targets related to solid biofuels production, it will be necessary to seek other sources of woody biomass. As a matter of fact, demand for wood fuels has increased in recent years, and enlargement and differentiation of the suppliers are necessary (IEA, 2006). According to Smeets and Faaij (2007), biomass from conventional forestry should satisfy the needs of both forest industries and wood energy producers. Hence, woody biomass from mountain forests might fulfil the enhanced demand for wood fuels and promote socio-economic development. New sources of income and working opportunities in both forestry and the bioenergy sector can be generated for mountain communities. Furthermore, forestry in mountainous areas has a long tradition. In the past, the timber harvested in these areas had predominantly domestic uses (construction, heating, cooking and livestock fodder). However, during the last decades socioeconomic changes in European society has led to the abandonment of mountain land, causing a net increment of forest growth. The harvest of wood fuel from these areas can be a strong motivation for reviving standing up against these past activities. Examples of European countries with many mountain forests matching the above-mentioned description are Norway and Italy.

1.2 Objectives

The overall objective of the study is to analyze and compare case studies related to the GHG emissions of two mountain forest wood fuel supply chains (MFWFSCs) in Norway (case study A) and Italy (case study B).

Specific objectives are:

- to perform a LCI (Life Cycle Inventory) of inputs and outputs required for wood fuel production;
- to perform a LCA (Life Cycle Assessment) of GHG impact of MFWFSCs;
- to analyze the net GHG benefits at the plants when wood fuel substitutes fossil fuels;
- to perform a cost analysis and analysis of employment of MFWFSCs;
- to analyze and compare different techniques for treating forest fuels;
- to highlight the most sensitive processes along the mountain forest supply chain;
- to analyze and compare the main findings of the Norwegian and Italian case studies, identifying differences, similarities and dominant trends.

Two parts constitute the thesis. The first part consists of this synthesis. General concepts concerning bioenergy are presented in chapter 1. A description of both mountain forest characteristics and their relationship with bioenergy, and a presentation of the energy and forestry situation of Norway and Italy are illustrated in chapter 2. The main methods and material used in the studies are discussed in chapter 3. Chapter 4 reports a synthesis of the articles. Main findings from all papers together with conclusions and future research are discussed in chapter 5. Specification of main input data assumptions for paper 1, 2 and 3 are presented in appendix. The second part of the thesis consists of four independent articles.

The PhD project aims to increase knowledge regarding:

- GHG impacts of MFWFSCs;
- research of alternative sources of woody biomass for bioenergy purposes;
- comparison of experiences from resource utilization in mountainous forests in two contrasting countries.

CHAPTER 2
BACKGROUND

2.1 Mountain forests

Mountain regions occupy 24% of the world's surface, and 28% of the world's forests. Around one tenth of the global population live in mountain areas (Price, 2003). A high human population density characterizes European mountain forests, especially in Southern Europe, compared to other parts of the world. Mountain forests have various functions: protection against natural hazards and erosion, water capture, source of fresh water, landscape, recreation, biodiversity conservation, etc. They also furnish different services as timber, wood fuel and non-wood products for both mountain and plains populations (Butt and Price, 2000). Policy programs and national legislation recognize the environmental services of mountain forests. According to FAO (2011), European forested land has increased in the last century. In Europe, more than one quarter of the forests is located in mountain forests (Glück, 2002), where a spontaneous process of reforestation, especially in sites formerly used for grazing and agriculture, has occurred (Piussi, 2000). Examples of this phenomenon can be seen in two mountainous countries Norway and Italy, where an annual increment of forest growth has been registered (Kräuchi et al., 2000).

Mountain forests are often unique and sensitive ecosystems. Climate change, especially change in temperature, has a strong influence on European mountain ecosystems. An increment of annual average temperature it is expected in the end of this century and in the Mediterranean areas, this trend is accelerated (Christensen et al., 2007). A shift in the timberline at higher altitude is one predictable consequence. However, beside negative effects of the increase of biotic and abiotic disturbance, the shift of tree line at higher altitudes can have positive effects on the increment of wood availability for different purposes such as bioenergy. Greater variability in the species composition and even an increment in biodiversity are possible (Maroschek et al., 2009). However, mountain forest ecosystems are not resilient to overexploitation and respond slowly to disturbance (Glück, 2002). There are substantial differences between mountain and lowland forests regarding ecological, economical and social aspects. At high elevation, forests are characterized by different species composition, and forest dynamics (regeneration, growth, etc.) are slower than at lower elevation. At this altitude the distribution of the vegetation is particularly sensitive to climate conditions and productivity is limited by lower temperatures, shallower soil and diversity in moisture regimes compared to lowland forests (Dotta and Motta, 2000; Price, 2003). Mountain forests are generally less productive and less profitable. However, the use of bioenergy may prevent a warmer climate because of the decrease in CO_2 emissions. Beyond that, forest operations also represent one of the few sources of employment and income generation.

2.2 Country background

2.2.1 *Norway*

In Norway, 40% of the land area is forested (SSB, 2011a), of which 30% is mountain forests (Hannerz, 2003), located in Hedmark and Oppland counties in particular. Norway is not member of the European Union. It is self-sufficient in energy, with domestic energy consumption being dominated by electricity, mainly based on hydropower (99%). Currently, crude oil and natural gas are valued at almost 50% of all exports (SSB, 2011b). In Norway, bioenergy has a small share of the domestic energy consumption (6%). Firewood for heating private households constitutes the main use of bioenergy. District heating is not so common in Norway and pellet production is low (IEA, 2009). The average size of forest property in Norway is around 50 ha, but is larger in Oppland and Hedmark counties being 70 ha and 120 ha respectively (SSB, 2011c). The national goal for GHG emissions, according to the Kyoto Protocol, is to increase emissions by one percent compared to the 1990 level by 2008-2012 (SSB, 2011d).

2.2.2 *Italy*

Forests, of which 60% are located in mountains, cover 30% of the Italian land (Croitoru et al., 2005). Italy, a member of European Union, is not self-sufficient in energy and is one of the largest importers of energy in Europe. Domestic energy consumption is mainly based on imported fossil fuels, principally petroleum and gas (77%) (ENEA, 2010). 8.2% of the total energy production is based on renewable energy sources dominated by hydroelectric power and geothermal sources (IEA, 2010). Instead, bioenergy accounts for a small share of renewable energy production. Wood fuels are used mainly for heating households although the pellet market is in expansion. Within Europe, Italy is the largest importer of pellets, especially in mountainous areas of Northern Italy (IEA, 2009). The Italian national Kyoto Protocol target is to reduce GHG emissions by 6.5% compared to the base year 1990 by 2008-2012 (IEA, 2010). The average forest property size is 7.5 ha, with 15% of properties smaller than 1 ha. In Trentino-Alto Adige region, in contrast to other Italian regions, the forest properties are mainly public (76% of the total forest properties) with an average size of 950 ha. Nonetheless, small properties characterize private forests (Dellagiacoma, 2006). The region of Trentino-Alto Adige constitutes a special case within Italy. It is an autonomous region, having a devolved fiscal system and specific administrative and management competences that are wider than in other Italian regions. These facts, together with high welfare standards, make it more comparable with Norwegian conditions.

2.3 Previous literature

2.3.1 *Forestry studies and life cycle assessment*

LCA is a common method used for evaluating the impacts of forest operations. In Sweden, Berg (1997) analyzed the use of fossil fuels for different forestry operations though the LCA methodology, Berg and Lindholm (2005) highlighted the most relevant processes in terms of emissions and energy use of forest operations for timber production in different parts of Sweden, and Athanassiadis (2000) analyzed and calculated the emissions and energy use of forest mechanized systems during logging operations.

In Finland, primary energy and long-distance transportation were studied by Karjalainen and Asikainen (1996), while Berg and Karjalainen (2003) compared the GHG emissions of forest operations between Sweden and Finland. In Norway, Michelsen et al. (2008) performed a hybrid LCA of GHG emissions, including a costs analysis.

In other parts of Europe, Schwaiger and Zimmer (2001) have compared fuel consumption and related GHG emissions of forest operations from different European countries. In USA, Sonne (2006) and Johnson et al. (2005) provide GHG inventories from forestry operations.

Concerning studies on wood fuel supply chains, LCA and environmental impacts, several studies come from Sweden. A life cycle inventory of emissions and energy use of bioenergy transport chains were calculated for each step of the supply chain by Forsberg (2000). Lindholm and Berg (2005) studied the environmental performance and energy consumption of long distance in timber transport systems using different source of energy, including biofuels. Gonzales-Garcia et al. (2009) performed a LCA of the environmental impacts of wood transport systems in Sweden and Spain for pulpwood production, simulating different scenarios. In Norway, Raymer (2006) performed LCA of GHG impacts of wood products and wood based bioenergy without including the forestry operations.

Most of the studies from South Europe in LCA were connected to short rotation forestry (e.g. Gasol et al., 2009), or dedicated agricultural energy crops (like e.g. Chiaramonti and Recchia, 2010). Only one study from Italy is found concerning the LCA of environmental impacts, including GHG emissions, for biomass combustion in domestic firewood and CHP plant in Lombardia region (Caserini et al., 2010).

2.3.2 *Examples of studies of forest fuel supply chains*

In Belgium, Van Belle et al. (2003) examined the methods for providing wood resources to power plants. In Austria, Kanzian (2009) described how to optimize a local energy wood supply chain. In Austria (Gronalt and Rauch, 2007) and Italy (Emer et al., 2011) models of wood fuel supply chains have been presented. Cherubini et al. (2009) made an energy balance and GHG balance of forest residues supply chain compared to a reference system based on fossil fuel. In Finland, Wihersaari (2005) evaluated GHG emissions of forest supply chains based on wood chips. Eriksson and Gustavsson (2008) studied and compared different supply chains based on wood chips, bundles and stumps. Wood chip and bundle system supply chains were studied by Eriksson and Gustavsson (2010) in Sweden and Finland. Lindholm et al. (2010) studied the energy efficiency and the environmental impacts, including GHG emissions, of harvesting logging residues. In Finland, Kärhä (2011) and Hakkila (2004) studied the production flow of wood chips. Tahvanainen and Anttila (2011) evaluated costs of long distance transportation for wood fuel by railway.

2.3.3 *Originality of the study*

So far, this study is the first one regarding life cycle assessment of mountain forest wood fuel supply chains and a comparative analysis between Norway and Italy, where mountain forests are important ecosystems. The previous studies concern supply chains from lowland forests in flat terrain. Some of these studies focus the attention mainly on one aspect of the supply chain such as logistical or technical aspect, while this study deals with different facets of the supply chain: environment, energy use, socio-economic, technical and logistical aspects. In most of the studies, logging residue harvesting is not integrated into the conventional forest operations. Another difference is that very few of the previous studies have included an analysis of costs.

CHAPTER 3
METHODS AND MATERIAL

3.1 LCA

LCA is a well-established and known methodology originally created in the 70s as industrial approach for following a product (packaging) from cradle (extraction) to grave (its disposal). In the mid 1980s, public opinion became more and more focussed on environmental issues, so environmental aspects were included into the LCA. In the 1990s, SETAC (Society for Environmental Toxicology and Chemistry) developed and created a framework for harmonizing the LCA studies (Hanssen, 1999). Hence, LCA became the tool for assessing natural resource requirements and environmental impacts of the whole process involved in the manufacture of a product, service or activity (Baumann and Tillman, 2004). Four phases characterize the LCA:

1. goal and scope definition;
2. Life Cycle Inventory, i.e. inputs and outputs of product system;
3. Life Cycle Impact Assessment;
4. interpretation of the results.

While several other methods for evaluating environmental impacts, listed in table 1 following the description of Finnveden and Moberg (2005), exist, LCA was the methodology chosen in this PhD study.

Table 1: Alternative and complementary methods to LCA and their main objectives

Objectives	Methodology
Natural resources and environmental impacts	Environmental Impact Assessment, Strategic Environmental Assessment and Environmental Managements Systems
Environmental auditing	Environmental Management System
Natural resources inputs	Material Flow Accounting, Ecological Footprint and Emergy Analysis
Cost associated to environmental impacts	Life Cycle Costing, Cost Benefit Analysis and Input-Output Analysis

The drivers behind this choice were: extensive description of a whole product cycle including the supply system, quantification of the results in relation to the same function and independently by specific site and comparison between production systems and other studies. LCA is a method under development and there is not a unique way for performing a LCA. International standard as ISO 14040, ISO 14044 (ISO, 2006a, 2006b) produced guidelines, but they do not state how to carry out a LCA for a specific product. Furthermore, LCA is adapted to assess a product in quantitative terms making it difficult to assess qualitative impacts such as biodiversity and land use changes (Wessman et al., 2003).

According to several authors such as Baumann and Tillman (2004), Cherubini et al. (2010), Lindholm et al. (2010), LCA is strictly dependent on specific choices:

1. functional unit (measure of the function of the studied system and reference unit for inputs and outputs assessed in the LCA);
2. system boundary (delimitation of the studied process system and identification of the unit process) and allocation;
3. data quality;
4. impact assessment method.

Studies in the bioenergy sector require particular emphasis on key choices related to raw materials sources, the combustion technique and reference system. Functional unit and the system boundary defined the scope of the LCA. The *functional unit* was one solid cubic meter over bark (1 m^3 s.o.b.) of wood fuel delivered from mountainous forest stands to the biomass combustion plant. Solid cubic meter is a common unit used in the forestry sector. Bark was included due to its value in the bioenergy sector (Kofman, 2010). The *system boundary* was the mountain forest wood fuel supply chain (MFWFSC); i.e. a network of unit processes (the smallest element considered in the LCI for which input and output data were quantified). The term supply chain indicates the steps involved in the bioenergy production from forest stand to the user, including wood fuel combustion. In the LCI, the inputs calculated were raw materials (m^3 s.o.b.) and fuel consumption (liter). Outputs, calculated per functional unit, were emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in kg and energy use in kWh.

The environmental impact category under assessment was climate change, where the characterization factor was global warming potential (GWP) with a time horizon of 100 years (IPCC, 2006), expressed in $kgCO_2$ equivalent ($kgCO_{2e}$) per functional unit.

3.1.1 *Calculations*

GHG emissions were calculated as a product of fuel consumption of each unit process of MFWFSC and emissions factors. In paper 2, 3 and 4, a GHG balance was achieved by the sum of emissions from the supply chain and bioenergy plant minus the emissions avoided thanks to the replacement of a fossil fuel plant. Energy use was calculated as the product of fuel consumption and energy content of fossil fuel. Energy balance or energy input-output ratio equals the energy use divided by energy output, i.e. the amount of energy released when combusting wood chips at the plant. The unit of measure for energy input and energy output was kWh, because it was related to the energy delivered to the combustion plant.

3.1.2 *Delimitation of the LCA*

LCA was performed for the supply system and not only for the products. In both case studies, logging residues harvest was integrated in the conventional forest operations. GHG emissions, i.e. CO_2, CH_4 and N_2O were calculated for each step of the supply chain, including combustion at the plant. All the emissions were loaded on existing technologies. In the thesis, assessment of combustion technologies, comparison with lowland forests (because traditional sources of raw materials), comparison with other renewable energy sources (because a less interesting reference system from a GHG perspective as compared with fossil fuel system) were excluded. Furthermore, road construction, maintenance, and transportation of forest workers to logging site, planning of forest operations, seedling production, and silviculture operations such as fertilization and chemical clearing, were not included in the study.

3.1.3 *Allocation*

An allocation of input and output of LCA has to be done when several products share the same production process, in this case: logging residues for energy and round wood for timber production. Hence, GHG impact should be expressed in relation to the different products. The challenge is to choose which share of the environmental impact, such as GHG emissions, should be allocated to the analyzed product (Ekvall and Finnveden, 2001). A possible way for avoiding allocation is the system expansion, where the boundary of the system is expanded to include the alternative production of an external product. When allocation cannot be avoided, additional functions of the co-products (i.e. timber and logging residues/wood fuels) are separated reproducing the way in which input and output are modified by quantitative changes in the products delivered (Baumann and Tillman, 2004). Input and output may be divided into the different products based on the mass output or some other type of relationship like economical value. Indeed, if bioenergy from mountain forests is considered as a by-product of timber production, all emissions should be loaded on timber production. Instead, when we think that wood fuel for energy is a product as well as round wood for timber production, it is advisable to allocate emissions based on the physical relationship using mass output as a criterion of allocation.

In case study A (paper 1), it was assumed to allocate 70% of emissions into wood fuel production and 30% into timber production, based on a physical causality approach as mass of outputs. Bundling was only allocated to the wood fuel production. For the transportation from the terminal to the combustion plants (paper 2) only wood fuels were transported which made it unnecessary to allocate either the input or the output. Regarding case study B (paper 3), GHG emissions generated from felling and extraction were charged in relation to the total volume of roundwood and logging residues. Later GHG emissions produced by chipping and chip transportation were allocated only to the logging residues component used for energy purpose, while the timber production chain was excluded by the study. At the DHP, emissions were loaded on wood chips from both logging residues and saw mill residues.

3.2 Case study

The case study is a scientific method used in several disciplines, such as social sciences, defined as: "*the detailed examination of a single example of a class of phenomena, a case study cannot provide reliable information about the broader class, but it may be useful in the preliminary stages of an investigation since it provides hypotheses, which may be tested systematically with a larger number of cases*" see Abercrombie (2006), page 34.

This technique is often criticized because of difficulties in making generalizations and developing theory based on a single case study and too much dependency on the study context (Flyvbjerg, 2006). However, these criticisms can be met to a certain degree.
It is possible to generalize, e.g., through an inductive approach. Generalization is based on the formulation of theory derived by data collected in the case study (Johansson, 2003). Generalization can produce scientific development. According to Zainal (2007) the concept of formal generalization is overestimated, while it is underestimated how one may draw general conclusions based on case studies. Consequently, the validity of theories based on case studies is not always site dependent.

The case study methodology has several positive sides:

- data are related to the conditions of the examined process and allow understanding of the study context;
- analysis of quantitative and qualitative aspects at the same time;
- explanation of not only real-life situation, but also of the complexity and interaction between different situations;
- comparison of case studies.

In this thesis, the case study methodology was chosen because of the few data and literature studies available for MFWFSCs.

3.3 Economic and social aspects

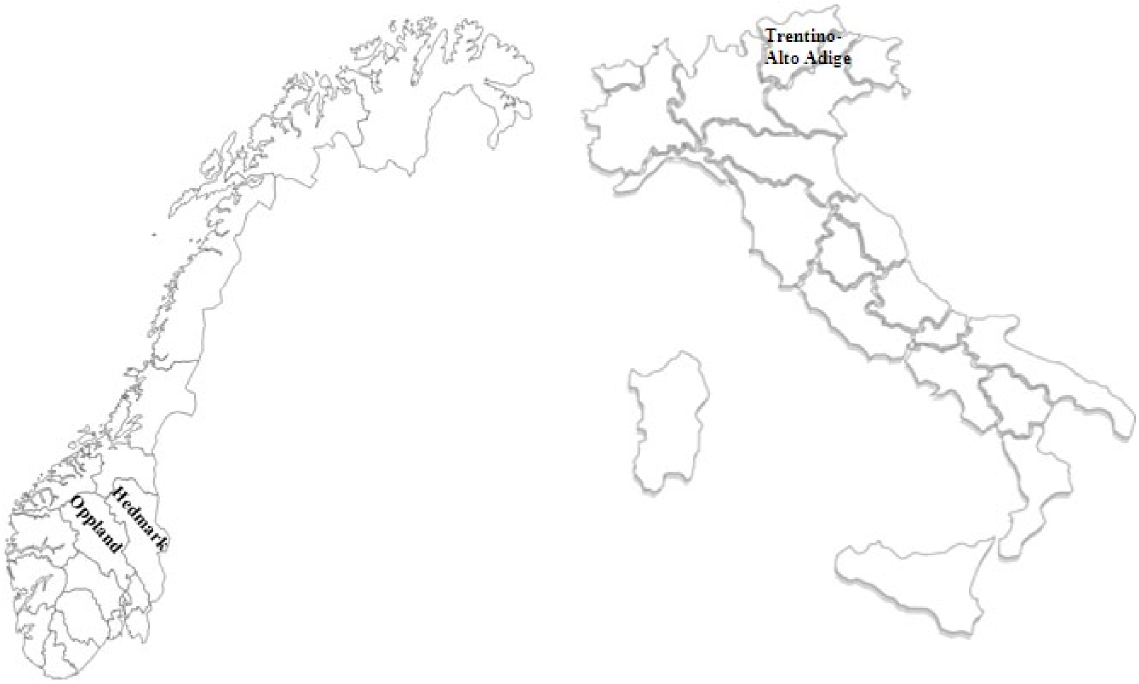
In the studies, beside the LCA, a cost analysis and an analysis of employment were performed. Regarding the cost analysis, production costs were calculated per functional unit (NOK/€ per m^3 s.o.b.). In case study A, costs of logging operations were defined based on forest productivity, tree density and forwarding distance of forest stands. In paper 1, only operative costs were included, i.e. costs related to hours of operation and use. In paper 3, case study B, costs were calculated as the sum of operative costs, plus overheads and profits. Operative costs were equal to the sum of fixed and variable costs. Fixed costs were independent of hours of operation, unlike variable costs. Hourly labour costs were included in the cost calculation based on the current national contract for forestry workers. Both case studies do not include subsidies. Costs at the bioenergy plant (paper 2 and 3) were not included in the analysis because of industrial secrets. In paper 2, costs of the wood chips at the bioenergy plant were obtained from the Swedish price list of wood chips, lacking the real costs. Regarding the social aspect, an analysis of employment was carried out only for the Italian case study, while data were missing for the Norwegian case. Direct employment potential was calculated as working hours per functional unit (h/m^3 s.o.b.). Costs and direct employment potential were allocated following the same principle used for GHG emissions.

3.4 Study area

Two case studies (figure 2) were carried out from mountainous sites in Norway (case study A - paper 1 and 2) and Italy (case study B - paper 3). In the present study, mountain forests were defined as forest stands dominated by coniferous species having a mature character, under specific altitude and terrain conditions. In the Norwegian case, mountain forest stands had an altitude between 700 and 1000 m a.s.l., flat terrain and a maximum harvest rate of 70% of the total standing volume (paper 1). In Trentino-Alto Adige region, Trento province, (Italy), the case study was performed in stands situated in Valle di Fiemme- having an altitude between 1500 and 1800 m a.s.l., in steep terrain with harvest rates between 35% and 70% (paper 3). Comparisons between different terrain conditions (flat and steep terrain) were justified by logging operations active during the data collection period.

Selective cutting, i.e. extraction of only part of the standing volume to maintain mixed aged forests, is the only harvesting system allowed in the studied mountain forests. The conventional forest management associated with selective cutting was natural regeneration.

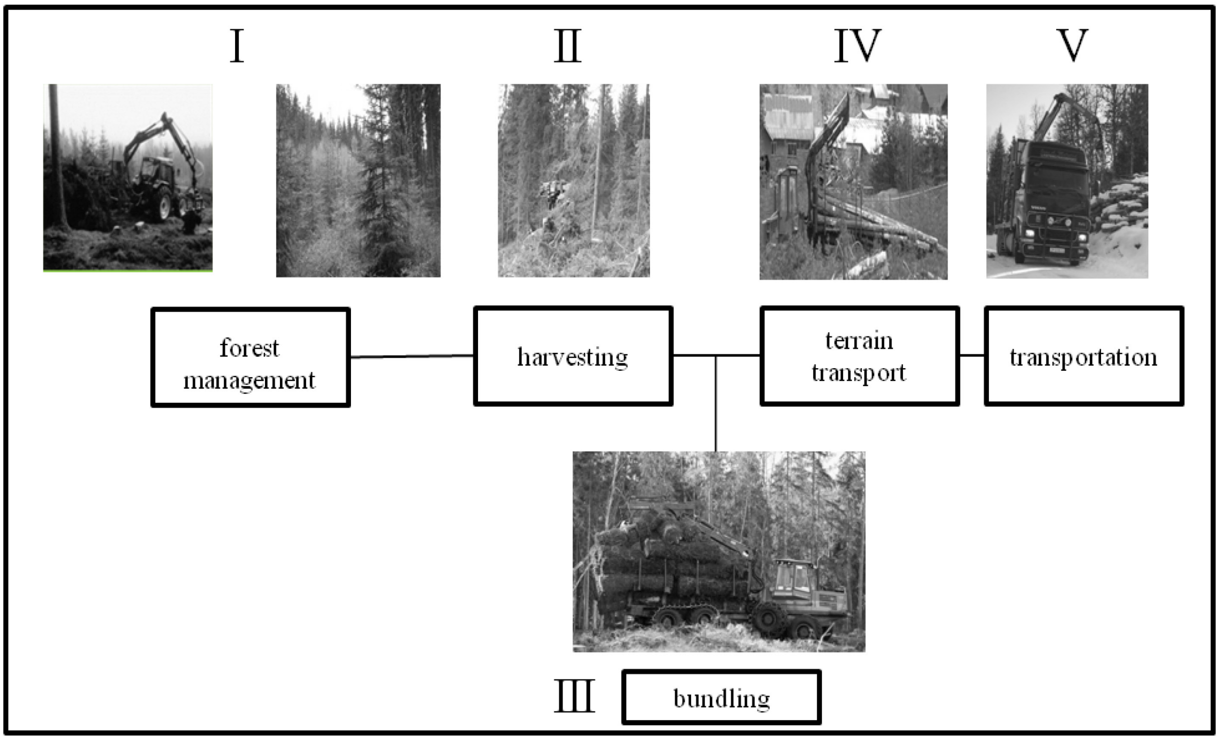
Figure 2: Map of case studies areas: Hedmark and Oppland counties (Norway) on the left and Trentino-Alto Adige region (Italy) on the right side.



3.5 Mountain forest wood fuel supply chains

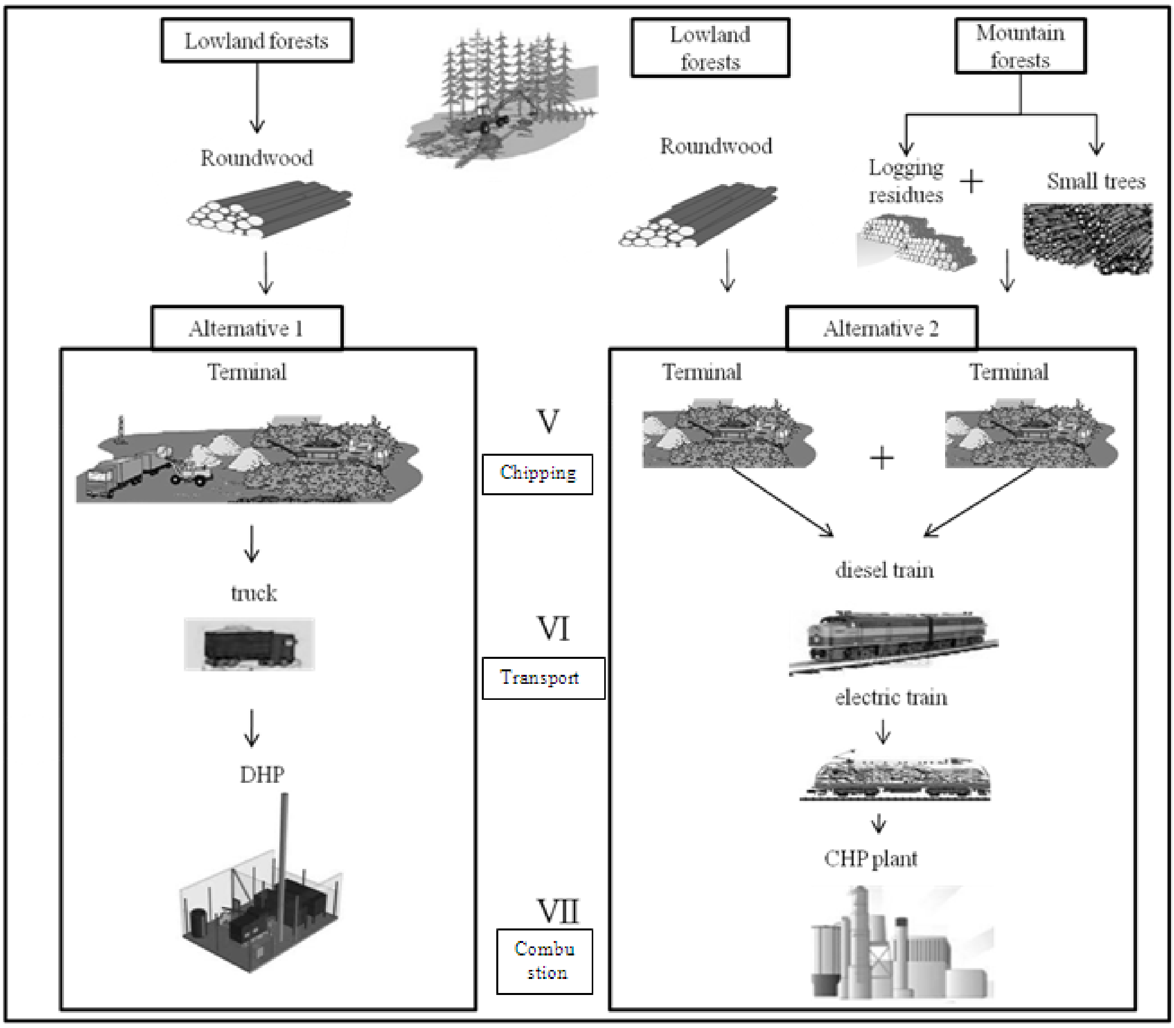
Figure 3, 4 and 5 show the wood fuel supply chains from Norwegian and Italian mountain forests. The Norwegian supply chain (case study A) was divided in two parts: part I (paper 1) from the cradle (forest stand) to the gate (terminal) and part II (paper 2), from the gate (terminal) to the user (bioenergy plant). Instead, a unique study –from cradle to user- was performed for the Italian supply chain (paper 3). A description of each supply chain is reported below each figure.

Figure 3: System boundary of the Norwegian wood fuel supply chain: case study A- part I



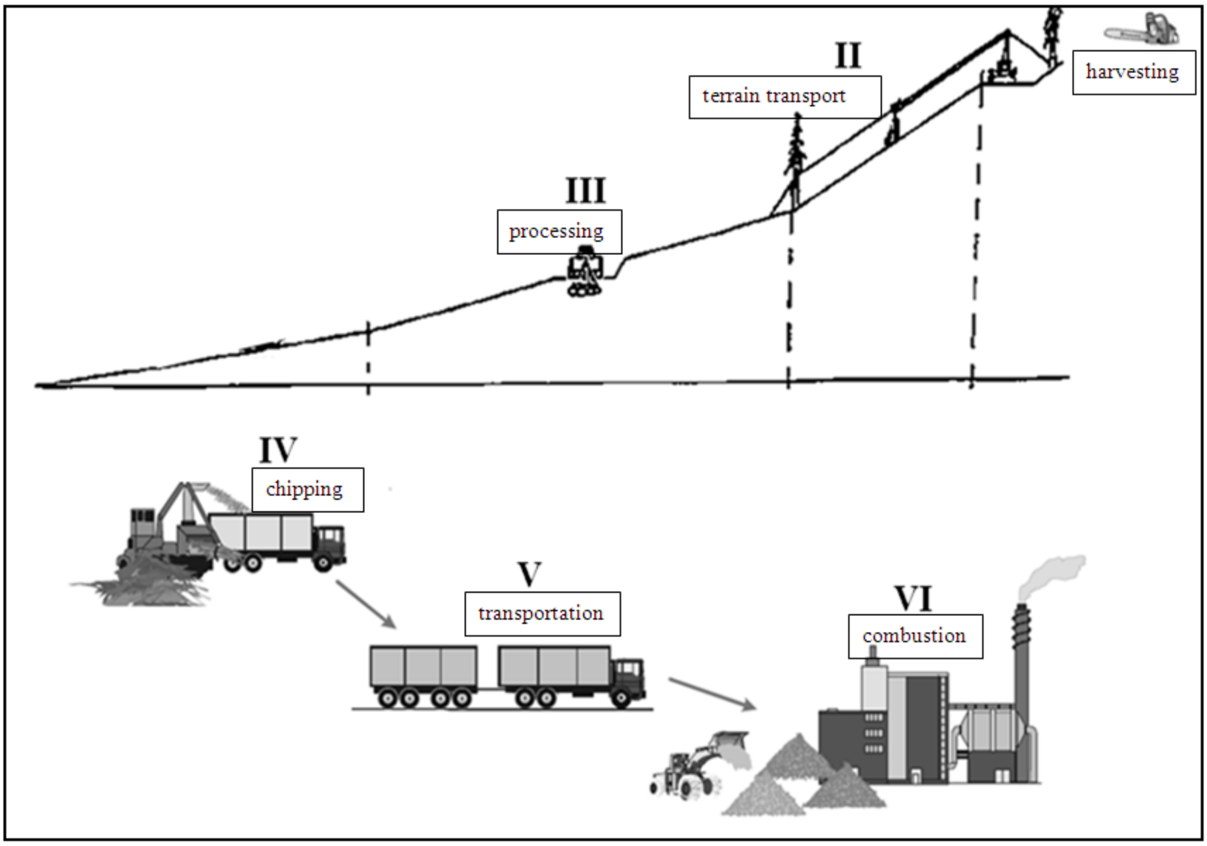
The supply chain started with forest management of forest stands (I) through soil scarification (silviculture) and planting (regeneration) and continued with harvesting (II) and forwarding (IV) of round wood. Logging residues were assumed to be harvested and bundled (III). The supply chain ended with transportation of round wood and bundles by conventional timber truck to the terminal (V).

Figure 4: System boundary of the Norwegian wood fuel supply chain: case study A-part 2



The second part of case study A had two alternatives. In alternative 1 (local supply chain), raw materials from local lowland forests were chipped at the terminal (VI) and transported by truck for a short distance (VII) to the user - DHP (VIII), where wood chips were combusted for producing heat to distribute to residential areas. Instead, in alternative 2 (international supply chain) raw materials constituted round wood from lowland forests and logging residues (bundles of case study A-part I) and small trees from mountain forests. All the woody biomass was chipped at terminals (VI). Wood chips were first loaded on a diesel train up to the border with Sweden and thereafter on an electric train (VII) to a Swedish CHP plant (VIII) for combustion.

Figure 5: System boundary of Italian wood fuel supply chain: case study B



The Italian system was the whole tree system (WTS), where the whole trees were felled by chainsaw at the stump site (I), extracted by cable yarder (II) and delimbed, bucked and stacked by excavator mounted processor at the landing site (III). Here, round wood was separated from logging residues. The latter were chipped at the landing (IV) and transported by chipper truck (V) for 30 km to a local DHP (VI) for combustion. The WTS was innovative compared to the traditional short wood system (SWS) used in Italy, where only the round wood is extracted by cable yarder and logging residues are left at the forest stand.

3.5.1 *Data and data source*

Reliable quantity data was necessary for carrying out the LCI and quantifying the inputs and outputs of each unit process. The data sources and their quality were variable and reported below, according to the goal of the study and the availability.

- field work for characteristics of forest stand and logging operations: case A and B;
- forestry companies (Mjøsen and Glommen): case A;
- public department of State Forest Administration of Paneveggio: case B;

- local municipalities: Fylkesmannen i Hedmark (case A) and Provincia di Trento (case B);
- bioenergy plant: Børstad (Hamar) and Skoghall mill (Karlstad-Sweden) in case A and Bioenergia Fiemme spa (Cavalese) in case B;
- literature studies (case A and B).

3.5.2 *Sensitivity analysis*

Sensitivity analysis was carried out to evaluate how changing the input parameter values can influence the results and pointing out the most critical unit processes along the wood fuel supply chain. Fuel consumption was the increased and decreased input parameter in paper 2 and 3 for identifying the effects on energy use and GWP respectively. In paper 3, labour cost was the changed input parameter for verifying the impacts on the overall costs. In paper 1, GHG emissions and costs were increased and decreased one at time for each unit process.

CHAPTER 4
RESULTS

Paper 1: Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain

Paper 1 is a case study from Hedmark and Oppland counties, where GHG emissions and costs of forest management (silviculture and regeneration), harvesting, terrain transport and transportation to the terminal were calculated. The system was expanded, including the harvest of forest residues by a bundling operation. Raw materials, fuel consumption and primary energy were the studied input flow. Results indicated that in the analyzed supply chain, 17.6 kg CO_{2e} /m^3 s.o.b. was emitted in total and 463 NOK/ m^3 s.o.b. was the costs. Transportation to the terminal was the unit process with the highest share of emissions (31%) and costs (23%) due to high fuel consumption and a long transportation distance between the forest stand and the terminal. Silviculture and regeneration had high costs, but generated only 2% of the total emissions. Bundling accounted for 25% of total emissions and 19% of the total costs, due to the introduction of extra machinery in the supply chain and few logging residues available. GHG benefits of harvesting wood fuel were evaluated in paper 2. Sensitivity analysis confirmed our results related to emissions and costs of forest management, bundling and transportation to the terminal.

Paper 2: Greenhouse Gas Emissions, Energy Use and Costs of Wood Fuel Supply Chains in Scandinavia

A LCA was carried out for calculating GHG emissions and energy use of three wood fuel supply chains from lowland and mountain forest stands in Hedmark and Oppland counties. The wood fuel supply chain in alternative 1 was a local supply chain, where roundwood from lowland forests was chipped at the terminal and transported by truck to a local DHP. In the alternative 2, two different suppliers of raw materials were considered: lowland forests (round wood) and mountain forests (logging residues and small trees). The whole raw materials were chipped at the terminal and transported together by diesel train and later on electric train to a CHP plant in Sweden. The GWP was 32 kg CO_{2e}/m^3 s.o.b. for alternative 1, and 22 kg CO_{2e}/m^3 s.o.b. and 24 kg CO_{2e}/m^3 s.o.b., for alternative 2, corresponding to lowland and mountain forest supply chains, while the energy balance was equal to 4.8 %, 3.6 % and 4.3 % respectively. The local wood fuel supply chain had higher emissions and energy use compared to the alternative of export to Sweden. Transportation by railway and higher efficiency at the combustion plant (cogeneration of heat and power) made the international wood fuel supply chain a better alternative than the local supply chain regarding GHG emissions and energy use. The most sensitive steps of the supply chain to change in the value of fuel consumption were transportation by truck and chipping operation. The mountain forest wood fuel supply chain did not increase emissions and energy use drastically. Woody biomass for energy from mountain forests can be a great alternative for meeting the increased demand of wood fuels in Sweden. The benefit of using bioenergy in the combustion plant was clear, where wood chips substituted fossil fuel such as coal.

The cost analysis showed that the export of wood chips from Norway to Sweden was also the cheapest alternative.

Paper 3: LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy)

Paper 3 describes an Italian case study in Valle di Fiemme, Trento province. An alpine forest fuel system was assessed by the LCA methodology. Stump site operation, extraction, landing operation, chipping and transport to a local DHP were the considered unit processes. GHG emissions (kg CO_{2e}/m^3 s.o.b.), operative costs (euro/m^3 s.o.b.) and direct employment potential (h/m^3 s.o.b.) were calculated for each step of the supply chain. The WTS, an innovative system in the Italian Alps was compared to the traditional SWS. The total GWP of the alpine forest fuel system was 13.2 kg CO_{2e}/m^3 s.o.b., where chipping was the operation with the highest rate of emissions, followed by transportation. Regarding the costs, 42 €/m^3 s.o.b. was the overall cost, where extraction by cable yarder was the most expensive operation (13 €/m^3 s.o.b.), followed by chipping (10 €/m^3 s.o.b.). The benefits of using wood fuel instead of fossil fuel were evaluated at the DHP. 2300 ton CO_{2e} and 1700 ton CO_{2e} were avoided by substituting fuel oil and natural gas plant respectively. The energy balance showed that the production of logging residues required low energy input (less than 5%) for the amount of energy released by burning wood chips during the combustion process. Sensitivity analyses highlighted fuel consumption and labor cost as critical parameters and changes in their value significantly influenced the results of chipping and extraction operations respectively. By comparison, the stump site operation and landing operation were not sensitive to changes in fuel consumption and labor costs. Concerning the analysis of employment, transportation was the operation creating most job opportunities, followed by extraction. The SWS generated more jobs than the WTS when only the round wood harvest chain was considered. However, in the forestry sector, employment is a debated issue and needs further investigations.

Paper 4: Mountain forests wood fuel supply chains: comparative studies between Norway and Italy

Paper 4 compares the results related to GHG emissions, energy use and cost analysis for the Norwegian and Italian case studies, previously presented in paper 1, 2 and 3. Forest management was of low intensity in both case studies. The Norwegian MFWFSC was more mechanized than the Italian one, where motor manual operation was still prevalent. Positive sides of the mechanization were high productivity and reduction of costs, negative sides were the increase of fuel consumption. Hence, case study A has twice the emissions and energy use of case study B. In Italy, e.g., cable yarding had the lowest emissions along the supply chain, because it was mainly done manually. However, this operation was extremely costly, due to high labor costs. In both case studies, the energy balance was positive, less than 5% input for generating 100 units of energy output. Transportation by truck and chipping operations were the most critical unit processes and sensitive to changes in fuel consumption. A substantial difference between Norway and Italy was the harvest of flat terrain located in highlands (case A) against steep terrain (case B), where mechanization is limited. Logging residues, generally left at forest stand were bundled in the Norwegian case and chipped at the landing in the Italian case. In Norway, the supply chain with lowest emissions and costs implied: harvest of logging residues, chipping at the terminal, railway transportation for long distances and combustion at a CHP plant. Instead, in Italy local MFWFSC, where logging residues were chipped at the landing and transportated for a short distance by truck to a DHP, showed better performance. Specific environmental and economic conditions made it difficult to generalize however.

CHAPTER 5
OVERALL SYNTHESIS AND CONCLUSIONS

5.1 Main findings

The main findings in the two case studies of mountain forest wood fuel supply chains (Hedmark and Oppland counties in Norway – paper 1 and 2 and Trentino province in Italy- paper 3) and their comparison (paper 4) are presented and discussed below.

Some main forest management activities characterized mountain forest stands. In the Norwegian case, seedling production and planting had high costs. Nevertheless, in the long term, the reduction of planting may decrease carbon sequestration in the Norwegian case. In Italy, as mentioned above, mountain forests were left to natural regeneration, where continuous forest cover delays the introduction of mechanized systems. However, forest management can improve forest conditions and create both new sources of income for forest owners and jobs opportunities. The genetic improvement of trees, for example, and soil scarification can improve the quality of plants and even increase carbon capture because of better tree growth. According to IEA (2002), it is possible to manage a forest as a carbon sink and for bioenergy production at the same time, especially at a local scale. Forest management can also influence positively biodiversity. Mountain forest stands can be managed for both production and biodiversity purposes, introducing forest techniques that are less harmful for the environment. If we think that all mountain forests should be maintained as reserves, we should consider that this choice is not sufficient for keeping the mountain forest ecosystem dynamic (Bengtsson et al., 2000).

The integration of logging residues harvest into the conventional timber supply chain, as assumed in case study A and B, can influence the timber sector positively. Low prices for round wood, especially for small diameter wood, may lead to the abandonment of logging operations in mountain forests. Harvest of logging residues could be one possibility for promoting forest operations in these areas. In recent years, the demand for forest fuel has increased considerably in Europe and logging residues from mountain forests can be one option for meeting this demand, otherwise it could be necessary to find other wood fuel sources, which may have higher impacts on the environment.

The GHG benefits derived by emissions saved due to the replacement of fossil fuel by wood fuels were clear at the user plant, especially when wood chips substituted coal (case study A) or fuel oil (case study B).

The energy balance of the MFWFSC was positive. Energy input was slightly higher in case A than in case B due to more steps involved in the supply chain. Nevertheless, in both case studies, low energy input (below 5%) was necessary for producing energy from wood chips (energy output), comparable with previous results: 2-3% in Wihersaari (2005), 1.4% in Eriksson and Gustavsson (2008) and 1.4% also in Lindholm et al. (2010). However, all these authors reported an energy balance for lowland conditions, which were slightly lower than the one found for our mountain forest supply chains.

The sensitivity analysis showed that fuel consumption was a critical input parameter, dependent on several variables and so difficult to quantify. Changes in its value of only 10% influenced the GHG emissions level. Improved efficiency of forest machines and the skill of forest operators or the use of biofuel instead of fossil fuel may reduce the fuel consumption and so emissions and energy use.

Mechanization of forestry operations leads to higher productivity and lower costs than motor manual systems, as demonstrated by the comparison between WTS and SWS (case study B). In line with Berg (1997), we found that motor manual operations for felling and bucking generated lower emissions than mechanized operations. Forest machines such as harvesters or forwarders (case study A) and processors (case study B) increased GHG emissions and energy use compared to motor manual systems because of higher fuel consumption and energy use. In Trentino, part-time businesses of forest companies, with an average size of 2.3 workers (Pers.Comm., 2011a) and a low harvesting volume do not justify the purchase of processors and explain the persistence of motor manual work.

Bundling was one technique studied for handling logging residues (case study A). However, other ways for transporting logging residues should be considered. Actually, the choice of transport technologies is important for the cost reduction. The difference between wood fuel transportation is in the bulk density. Logging residues can be transported loose, compacted in bundles, or as wood chips. Compaction of forest residues increases the bulk density and this is a key factor for the reduction of costs. Different options of supply chains affect the choice of harvesting and processing technologies (Andersson et al., 2002). The location of chipping operation, for example, is a key element to evaluate. Chipping can be at the landing (case study B) or at the terminal (case study A), but also in the terrain or at the source. In Finland, for example, Kärhä (2011) reported that wood chips from logging residues come mainly from roadside chipping and chipping at the plant, even though he predicted an increase of chipping at the terminal. Nonetheless we should emphasize that the efficiency of the production system depends strongly on site-specific environmental conditions and infrastructures (Hakkila, 2004).

In Norway, large-scale operations such as bundling are probably easier in large forest properties, where forest owners can share the transportation costs of forest machines. In the Italian Alps, generally, steep terrain, fragmentation and small dimensions of forest properties and management based on continuous cover forestry have delayed the introduction of mechanization, causing a persistence of motor manual operations, having low productivity and a high labour demand (Montorselli et al., 2010). Even in Trento province, where public properties are large and managed, the road infrastructure is not adapted to mechanization and steep terrain is main limit to its development. Forestry roads are too narrow for transporting machines such as processors at the landing. With slopes over 40%, as in case study B, it is technically and economically impossible to use forwarders and harvesters. Nonetheless, in Trentino, the number of processors has increased in recent years (Pers.Comm., 2011a). Mechanization is a new phenomenon in Trentino compared to Nordic countries and is quickly establishing.

A local supply chain and short transport distance by truck prevailed in the Italian case (case study B). Currently, Italy is a net importer of pellets. In the near future, we can presume domestic pellet production from sawmill residues and wood chip production from logging residues from local mountain areas will develop. Indeed Caserini et al. (2010) found exploitation of wood residues from tree management and saw mills were preferable to other alternatives. In this way, alpine areas can become self-sufficient in wood fuel.

The international supply chain was preferable in the Norwegian case. At present, export of wood chips from Norway to Sweden was profitable in terms of both GHG emissions and costs. Transportation by railway and a CHP plant made the international supply chain more efficient than the local supply chain (transportation by truck and DHP). Furthermore, it was economically more convenient to export wood chips than process them locally. However, local supply chains can become a feasible alternative when more efficient combustion plants such as CHP plants are built in Hedmark and Oppland counties and transport logistics improved.

Railway transportation based on electrified line made the supply chain more efficient and less air polluting, especially when hydroelectric energy is used, than transportation by truck (case study A). This conclusion is confirmed by the results of Tahvanainen and Anttila (2011): the most competitive alternative for long distance transportation (over 160 km) was transportation of wood chips to the terminal by truck and then by train to the plant. In the near future, it might be possible to improve the Italian railway line and transport wood chips from Trento province to other regions such as Lombardia, which has a high wood fuel demand.

Existing technologies were studied concerning combustion plant and boiler type. The Swedish CHP plant showed the benefit that beside producing electricity, it was possible to use the heat for either steam or district heating production. In this way, the efficiency of CHP plant influenced positively the efficiency of the whole supply chain. Furthermore, as confirmed by Caserini et al. (2010), CHP plants showed better environmental performance than DHP, because of the presence of extensive flue gas treatment in the formers.

The social aspect, i.e. the analysis of employment as working hours, was a critical point in case study B. Mechanization reduced the labour costs, was more productive and less worker demanding as confirmed by the comparison between SWS and WTS (paper 3). This concept can be extended to the Norwegian case, as highlighted in paper 4. In both Norway and Trentino-Alto Adige region, the social costs due to unemployment were low, while the labour cost was high. According to the national contract for forest workers in Italy and personal communication by a Norwegian forest company (Pers.Comm., 2011b) the labour costs were respectively 21 €/h and 26 €/h.

In case study A, income and employment in rural areas were difficult to calculate. Small forest owners harvest firewood as a part-time business (Pers.Comm., 2011c). In Italian mountain areas, as well as Norway, firewood is the main source of wood for heating. However, pellet stoves are a new and successful heating source in Italy, especially for new users who like the comfort and the economic convenience of pellets. In Italy, several manufacturers of stoves have started producing wood stoves that burn pellets.

At present, the MFWFSCs are not profitable compared to existing fossil fuel chains. It is necessary to have a more stable bioenergy market and greater investment in efficient and productive technologies. In Sweden, for example, profitability is higher due to the introduction of strong economic incentives for replacing fossil fuel. Of course, one solution can be to introduce subsidies for harvesting mountain forest stands and investing into local bioenergy plants. Furthermore, the reduction of emissions is a key issue for the decision makers. Hence, European Union goals are pushing countries such as Italy to increase the use of bioenergy that is less costly, logistically easier and readily exploitable in the short term. In contrast, Norway, having a different energy situation and to some degrees different goals than the European Union, can develop other technologies to bioenergy, like the capture and storage of carbon (CCS) under sea.

5.2 Critical review of LCA, carbon neutrality and sustainability concepts

5.2.1 *LCA*

During this PhD study, the LCA methodology showed its limits. One limiting factor was the difficulty in finding data for some steps of the supply chain. Examples include the analysis of employment in case study A, and cost analysis of the user in case studies A and B. It was also challenging to make comparisons with other studies due to variability in terminologies, data collection, and analyses, and different sets of assumptions. The time and space frames were other key points to consider in the LCA. The time delimitation was important because it determines the persistence of the GHG impact on the atmosphere. In the present study, a GWP with 100 years as the time of decay of the GHG emissions was used. The choice of the time horizon can be classified as an ethical choice, because we consider 100 years as the length of the GHG impact on future generations (Finnveden, 2000). Shorter and longer time horizons can have a substantial impact on the results and conclusions.

Another key element was the space delimitation, i.e. how we defined and limited the system boundary. The main findings and results are based on the selected system boundaries, and the introduction of other unit processes such as road construction or transportation of forest operators to the stand could significantly affect the results and modify the conclusions.

Traditionally LCA is a tool for assessing environmental impact of a product, and not for socio-economic analysis. The author is aware of several efforts made for integrating the socio-economic dimension into LCA, see as Hoagland (2001), Cooper (2003), Klöpffer (2003), Ny et al. (2006), Ness et al. (2007), and combining Life Cycle Assessment (an environmental impact tool), Life Cycle Costing (an economic tool) and the Social Life Cycle Assessment (a social tool) into a unique tool. Emergy analysis might be an interesting alternative for covering ecological and socio-economic analysis at the same time, thanks to the quantification of a product and service independently by environment or economy (Rydberg, 2008).

5.2.2 *Carbon neutrality for bioenergy system*

The C neutrality concept is constantly under debate, see for example Schlamadinger and Marland (1996), Johnson and Curtis (2001), Johnson (2009), Marland (2010) and Sjølie (2011). Marland, e.g., listed four issues for accounting GHG emissions in a bioenergy system: accounting issue, a temporal issue, a linkage issue, and a uniqueness issue. The *accounting issue* means that *biomass energy is only truly carbon neutral if we get the system boundaries right;* see Marland (2010), page 866. This implies that it is important to decide how we should account for the CO_2 emissions and what we should include in our system boundary. By *temporal issue* he means that there is a difference in time scale between wood fuel combustion and the regrowth of the trees, as in the short term there is an increment of CO_2 emissions into the air that will be taken up when the forest grow again. By *linkage issue* he means the importance of considering the linkage between biological uptake of bioenergy emissions in time, space, and driving force. By *uniqueness issue* he means that decrease of emissions in one country can increase emissions in another country.

The carbon neutrality concept should be considered as a system in a holistic perspective, where not only a single forest stand, but also other elements such as forest products and timber construction should be included in the account of net carbon circulation.

5.2.3 *Sustainability concept*

The principle behind sustainable development is wider than the conservation of a static forest-system. Actually, if future generations are not cared the decision-maker should not be worried about a society based on fossil fuel. The author agrees with the precautionary principle, i.e. the mountain forest should be protected from degradation and overexploitation

(UN, 1992), but at the same time, it is fundamental to develop new systems for guaranteeing a sustainable future for the next generation, as affirmed in Brundland Report (WCED, 1987). Sustainability should be kept in all the phases of the bioenergy production (Thornley et al., 2009) with the purpose of climate change mitigation (Schubert and Blasch, 2010). We should maintain mountain forests in a good state, at least as good as in the initial period before harvest. Pros and cons of bioenergy utilization from mountain forests should be evaluated in a global perspective without any delimitation of time and space, also keeping in mind national policies and targets.

The use of forest resources for bioenergy purposes should work with and not against the mountain forest dynamics. The intention of this PhD research is to respect the equilibrium among environmental, economic and social aspects, increasing the welfare of mountain areas through the generation of new opportunities of employment and sources of income for local communities and diversifying goods to satisfy the new needs of society.

5.3 Ethics and conflicts of interests

Ethical questions can arise concerning the harvest of wood fuel from mountain forests. Public acceptance is another element to consider. Often society is sceptical towards the introduction of new systems or products in every-day life, in this case, energy supply based on wood fuels from mountain forests. Hence, it is fundamental to guarantee sustainable production and use of bioenergy, improvement of air quality and more in general living conditions. Conflicts of interests can come up due to the multi-functional role of mountain forests (for example tourism and recreation use against bioenergy utilization or bioenergy production against timber production).

5.4 Future research

Wood fuel from mountain forests has great potential in Europe. This project was based on case studies, but it is necessary to conduct additional and deeper analyses on aspects not treated in the thesis if we wanted to harvest woody biomass from mountain forests more intensively. It is important to estimate the real amount of wood fuel that can be harvested from the highlands in a sustainable way. Hence, we should assess the ecological impacts of implementing forestry operations on soils and biodiversity. Indeed, the removal of forest residues can cause depletion of nutrients and organic matter in the soil. In the future, a reduction in forest productivity and changes in biodiversity are predicted (Raulund-Rasmussen et al., 2008). For example, a lower availability of wood used as breeding substrate by saproxylic organisms could provoke habitat reduction and a risk of species extinction (Jonsell, 2007). Hence, we suggest evaluating the loss of biodiversity due to wood fuel harvesting. In the mountain forest, it may be hard to quantify the real amount of habitat loss that each single species can tolerate, but it is possible to develop guidelines for protecting the most threatened species and wood habitat types. Forest fragmentation due to harvesting is another issue to examine (Angelstam et al., 2002).

Also, further research will concern the effects of wood fuel harvest on soil organic matter in relation to the nutrient cycle. The levels of carbon and nitrogen in the soil are related to the intensity of harvest and the type of forest management (Johnson, 2001). Hence, it is important to study which type of forest management is most suitable for mountain areas. Indeed, according to Matala (2009) the type of forest management affects the carbon stock. Based on experience from other Scandinavian countries, one solution for counteracting the loss of nutrients is ash recycling. In Italian Alps, law forbids the latter and it is difficult to spread ashes in steep terrain not accessible to tractors. As recommended by Cherubini (2010), changes in carbon stock in the soil should be included in the calculation of GHG balance of the analyzed bioenergy system.

It is important to understand how changes in land use can impact the total carbon cycle of mountain forests (Schlamadinger and Marland, 1996). In the last years, land use change together with biodiversity has become an increasingly important issue in bioenergy assessments. Nevertheless, LCA does not deal with these qualitative aspects, hence other methodologies, such as environmental impact assessment analysis, can be used for assessing biodiversity (Burgess and Brennan, 2001).

In future studies, other impact categories such as acidification and natural resource depletion might be assessed, included and weighted. Weighting means than each impact category is expressed as its single contribution to the total environmental impact. If possible, a single score might aggregate the total environmental impacts from different impact categories.

Another topic of study can be the comparison between the alternative of using wood fuels from highlands (future source) with lowland forests (current source). Bioenergy can be compared to other renewable energy sources, such as solar energy in Italy and wind energy in Norway.

Future research is also need on how to improve the efficiency of the mountain forest wood fuel supply chains, and to test and identify the best technologies and technical solutions adapted to mountain conditions. Very few previous LCA studies have included cost analyses in the analysed systems. In my opinion, it is important to include costs in such analyses, to get a better understanding of what is feasible economically. This will also create a bridge between pure technical/environmental analyses and considerations of the market possibilities, which is vital information for decision making in public policy as well as for the industries.

Deeper analyses of social aspects are suggested, although often quite challenging and site specific (Domac et al., 2005).

Finally, the knowledge achieved from this study should be communicated to both society and policy makers for putting in practise our findings and widening the use of wood fuels from mountain forests.

PERSONAL COMMUNICATIONS

Pers.Comm., 2011a. Provincia Autonoma di Trento (PAT), Servizio Fauna e Foreste.

Pers.Comm., 2001b. Severin Myrbakken, Forstkandidat Myrbakken. Data from Glommen SKOG BA.

Pers.Comm., 2011c. Runa Elisabeth Skyrud, Fylkesmannen i Hedmark.

REFERENCES

Abercrombie, N., Hill, S., Turner, B.S., 2006. Dictionary of sociology. Penguin, UK.

Andersson, G., Asikainen, A., Björheden, R., Hall, P., Hudson, J., Jirjis, R., Mead, D., Nurmi, J., Weetman, G., 2002. Production of Forest Energy in: Richardson, J., Björheden, R., Hakkila, P., Lowe, A. T., Smith, C. T., (Ed.), Bioenergy from Sustainable Forestry Guiding Principles and Practice. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 49-123.

Angelstam, P., Mikusinski, G., Breuss, M., 2002. Biodiversity and forest habitats, in: Richardson, J., ; Bjorheden, R., Hakkila, P, Lowe, A.T., Smith, C.T., (Ed.), Bioenergy from Sustainable Forestry: Guiding Principles and Practice. Dordrecht, The Netherlands, pp. 216-43.

Athanassiadis, D., 2000. Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. The Science of The Total Environment 255 (1-3), 135-43.

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Studentlitteratur, Lund, Sweden.

Bengtsson, J., Nilsson, S.G., Franc, A., Menozzi, P., 2000. Biodiversity, disturbances, ecosystem function and management of European forests. Forest Ecology and Management 132 (1), 39-50.

Berg, S., 1997. Some aspects of LCA in the analysis of forestry operations. Journal of Cleaner Production 5 (3), 211-7.

Berg, S., Karjalainen, T., 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry 76 (3), 271-84.

Berg, S., Lindholm, E.-L., 2005. Energy use and environmental impacts of forest operations in Sweden. Journal of Cleaner Production 13 (1), 33-42.

Burgess, A.A., Brennan, D.J., 2001. Application of life cycle assessment to chemical processes. Chemical Engineering Science 56 (8), 2589-604.

Butt, N., Price, M.F., 2000. Mountain people, forests and trees: Strategies for balancing local management and outside interests. Synthesis of an Electronic Conference of the Mountain Forum. April 12-May 14, 1999, Franklin, West Virginia, US.

Caserini, S., Livio, S., Giugliano, M., Grosso, M., Rigamonti, L., 2010. LCA of domestic and centralized biomass combustion: The case of Lombardy (Italy). Biomass and Bioenergy 34 (4), 474-82.

CEN, 2004. Teknisk specififikation SIS-CEN/TS 14588:2003. Solid biofuels- terminology, definitions and descriptions. Swedish Standard Institute, Stockholm, Sweden.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling 53 (8), 434-47.

Cherubini, F., 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. Renewable Energy 35 (7), 1565-73.

Chiaramonti, D., Recchia, L., 2010. Is life cycle assessment (LCA) a suitable method for quantitative CO2 saving estimations? the impact of field input on the LCA results for a pure vegetable oil chain. Biomass and Bioenergy 34 (5), 787-97.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A.,Whetton, P. , 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment

Report of the Intergovernmental Panel on Climate Change Regional climate projections. Cambridge University Press, Cambridge, UK, New York, USA.
Cooper, J.-S., 2003. Life-Cycle Assessment and Sustainable Development Indicators. Journal of Industrial Ecology 7 (1), 12-5.
Croitoru, L., Gatto, P., Merlo, M., Paiero, P., 2005. Italy, in: Merlo, M., Croitoru, L. , (Ed.), Valuing Mediterranean Forests – Towards Total Economic Value. CABI Publishing Wallingford, Cambridge, UK, 279-298.
Dellagiacoma, F., 2006. L'associazionismo forestale in provincia di Trento. Terra Trentina 6, 13-9.
Domac, J., Richards, K., Risovic, S., 2005. Socio-economic drivers in implementing bioenergy projects. Biomass and Bioenergy 28 (2), 97-106.
Dotta, A., Motta, R., 2000. Boschi di conifere montani - Indirizzi selvicolturali. Regione Piemonte, Blu edition.
Ekvall, T., Finnveden, G., 2001. Allocation in ISO 14041--a critical review. Journal of Cleaner Production 9 (3), 197-208.
Emer, B., Grigolato, S., Lubello, D., Cavalli, R., 2011. Comparison of biomass feedstock supply and demand in Northeast Italy. Biomass and Bioenergy 35 (8), 3309-17.
ENEA, 2010. Rapporto Energia e Ambiente. Analisi e scenari 2009. Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Roma, Italia.
Eriksson, L.-N., Gustavsson, L., 2008. Biofuels from stumps and small roundwood--Costs and CO2 benefits. Biomass and Bioenergy 32 (10), 897-902.
Eriksson, L.-N., Gustavsson, L., 2010. Comparative analysis of wood chips and bundles - Costs, carbon dioxide emissions, dry-matter losses and allergic reactions. Biomass and Bioenergy 34 (1), 82-90.
EU, 2009. Directive 2009/28/EC of the European Parlament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (23 April 2009). Official journal of the European Union, L 140, 16-62.
FAO, 2011. State of the World's Forests 2011. Food and Agricultural Organization.
Finnveden, G., 2000. On the limitations of life cycle assessment and environmental systems analysis tools in general. The International Journal of Life Cycle Assessment 5 (4), 229-38.
Finnveden, G., Moberg, Å., 2005. Environmental systems analysis tools - an overview. Journal of Cleaner Production 13 (12), 1165-73.
Flyvbjerg, B., 2006. Five Misunderstandings About Case-Study Research. Qualitative Inquiry 12 (2), 219-45.
Forsberg, G., 2000. Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method. Biomass and Bioenergy 19 (1), 17-30.
Gasol, C.M., Martínez, S., Rigola, M., Rieradevall, J., Anton, A., Carrasco, J., Ciria, P., Gabarrell, X., 2009. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable and Sustainable Energy Reviews 13 (4), 801-12.
Glück, P., 2002. Property rights and multipurpose mountain forest management. Forest Policy and Economics 4 (2), 125-34.
González-García, S., Berg, S., Feijoo, G., Moreira, M., 2009. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. The International Journal of Life Cycle Assessment 14 (4), 340-53.
Gronalt, M., Rauch, P., 2007. Designing a regional forest fuel supply network. Biomass and Bioenergy 31 (6), 393-402.

Hakkila, P., 2004. Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999–2003. Final report. National Technology Agency of Finland Helsinki, Finland, 29-49.

Hannerz, M., 2003. Forest research in the north. Scandinavian Journal of Forest Research News & Views 4 (18), 291-3.

Hanssen, O., 1999. Status of Life Cycle Assessment (LCA) activities in the Nordic Region. The International Journal of Life Cycle Assessment 4 (6), 315-20.

Hoagland, N., 2001. Non-traditional tools for lca and sustainability. The International Journal of Life Cycle Assessment 6 (2), 110-3.

Holmgren, K., Olsson, M., 2008. Biomass fuels not enterely climate-neutral - but better than fossil fuels, in: Johansson, B., (Ed.), Bioenergy-for what and how much? Forskningsrådet Formas, Stockholm, Sweden.

IEA, 2002. Bioenergy Task 38.Greenhouse Gas Balances of Biomass and Bioenergy Systems. International Energy Agency. Joanneum Research Forschungsgesellschaft, Graz, Austria.

IEA, 2006. Bioenergy Task 38 and 40. Options for Trading Bioenergy Products and Services. International Energy Agency. Joanneum Research Forschungsgesellschaft, Graz, Austria.

IEA, 2007. IEA Bioenergy 28th update. Biomass and Bioenergy 31 (5), 1-11.

IEA, 2009. Bioenergy task 40. Sustainable International Bio-energy trade. Country report 2009 for Norway, International Energy Agency:http://www.bioenergytrade.org/downloads/norwegiancountryreport09.pdf Visited on September 2011.

IEA, 2010. Energy Policies of IEA Countries - Italy- 2009 Review. International Energy Agency: http://www.iea.org/textbase/nppdf/free/2009/italy2009.pdf Visited on September 2011.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories.Agriculture, Forestry and Other Land Use. Intergovernmental Panel of Climate Change, Japan.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.), Geneva, Switzerland.

ISO, 2006a. International Organization for Standardization ISO 14040, 2006. Environmental management – Life Cycle Assessment – principles and framework. .

ISO, 2006b. International Organization for Standardization. ISO 14044: 2006. Environmental management – Life Cycle Assessment – requirements and guidelines.

Johansson, R., 2003. Case Study Methodology. Key note presented at International Conference “Methodologies in Housing Research" at Royal Institute of Technology, Stockholm, Sweden, 22–24 September 2003.

Johnson, D.W., Curtis, P.-S., 2001. Effects of forest management on soil carbon and nitrogen storage: Meta Analysis Forest Ecology and Management 140, 227-38.

Johnson, E., 2009. Goodbye to carbon neutral: Getting biomass footprints right. Environmental Impact Assessment Review 29 (3), 165-8.

Johnson, L., Lippke, B., Marshall, J., Comnick, J., 2005. Life-Cycle Impacts of Forest Resource Activities in the Pacific Northwest and Southeast United States. Wood and Fiber Science 37 (0), 30-46.

Jonsell, M., 2007. Effects on biodiversity of forest fuel extraction, governed by processes working on a large scale. Biomass and Bioenergy 31 (10), 726-32.

Kanzian, C., Holzleitner, F., Stampfer, K., Ashton, S., 2009. Regional Energy Wood Logistics – Optimizing Local Fuel Supply. Silva Fennica 43 (1), 113-28.

Karjalainen, T., Asikainen, A., 1996. Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 69 (3), 215-28.

Klöpffer, W., 2003. Life-Cycle based methods for sustainable product development. The International Journal of Life Cycle Assessment 8 (3), 157-9.

Kofman, P.D., 2010. Units, conversion factors and formulae for wood for energy. Harvesting / Transportation n.21. COFORD, Dublin, Ireland.

Kräuchi, N., Brang, P., Schönenberger, W., 2000. Forests of mountainous regions: gaps in knowledge and research needs. Forest Ecology and Management 132, 73-92.

Kärhä, K., 2011. Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy 35 (8), 3404-13.

Lexerød, N.L., Eid, T., 2006. Assessing suitability for selective cutting using a stand level index. Forest Ecology and Management 237 (1-3), 503-12.

Lindholm, E.-L., Berg, S., 2005. Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research 20, 184-91.

Lindholm, E.-L., Berg, S., Hansson, P.A., 2010. Energy efficiency and the environmental impact of harvesting stumps and logging residues. European Journal of Forest Research 129 (6), 1223-35.

Marland, G., 2010. Accounting for Carbon Dioxide Emissions from Bioenergy Systems. Journal of Industrial Ecology 14 (6), 866-9.

Maroschek, M., Seidl, R., Netherer, S., Lexer, M.-J., 2009. Climate change impacts on goods and services of European mountain forests. Unasylva 231/232 (60), 76–80.

Matala, J., Kärkkäinen, L., Härkönen, K., Kellomäki, S., Nuutinen, T., 2009. Carbon sequestration in the growing stock of trees in Finland under different cutting and climate scenarios. European Journal of Forest Research 128 (5), 493-504.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S., 2001. Climate change 2001: Impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, United Kingdom.

Michelsen, O., Solli, C., Strømman, A.-H., 2008. Environmental Impact and Added Value in Forestry Operations in Norway. Journal of Industrial Ecology 12 (1), 69-81.

Montorselli, N.-B., Lombardini, C., Magagnotti, N., Marchi, E., Neri, F., Picchi, G., Spinelli, R., 2010. Relating safety, productivity and company type for motor-manual logging operations in the Italian Alps. Accident Analysis & Prevention 42 (6), 2013-7.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecological Economics 60 (3), 498-508.

Ny, H., MacDonald, J.P., Broman, G., Yamamoto, R., Robért, K.-H., 2006. Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic. Journal of Industrial Ecology 10 (1-2), 61-77.

Parikka, M., 2004. Global biomass fuel resources. Biomass and Bioenergy 27 (6), 613-20.

Piussi, P., 2000. Expansion of European mountain forests, in: Price, M.F., Butt, N. , (Ed.), Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000. CABI International, Wallingford, pp.19-25.

Price, M.F., 2003. Why mountain forests are important. The Forestry Chronicle 79 (2), 219-22.

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callessen, I., Helmisaari, H-S., Karltun, E., Varnagiryte-Kabasinskiene, I., 2008. Effects on very intensive forest harvesting on short and long term site productivity, in: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I., (Ed.), Sustainable use of forest biomass for energy – a synthesis with focus on the Nordic and Baltic countries. Springer, Dordrecht, The Netherlands, pp. 28-78.

Raymer, A.K., 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass and Bioenergy 30 (7), 605-17.

Rydberg, T., 2008. Today's analysis methods create overconfidence in bioenergy, in: Johansson, B., (Ed.), Bioenergy-for what and how much? Forskningsrådet Formas, Stockholm, Sweden.

Sasaki, N., Knorr, W., Foster, D.R., Etoh, H., Ninomiya, H., Chay, S., Kim, S., Sun, S., 2009. Woody biomass and bioenergy potentials in Southeast Asia between 1990 and 2020. Applied Energy 86 (Supplement 1), 140- 50.

Sathre, R., Gustavsson, L., 2009. Using wood products to mitigate climate change: External costs and structural change. Applied Energy 86 (2), 251-7.

Schlamadinger, B., Marland, G., 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 10 (5-6), 275-300.

Schubert, R., Blasch, J., 2010. Sustainability standards for bioenergy-A means to reduce climate change risks? Energy Policy 38 (6), 2797-805.

Schwaiger, H., Zimmer, B., 2001. A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe, in: Karjalainen, T., Zimmer, B., Berg, S., Welling, J., Schwaiger, H., Finér, L., Cortijo, P., (Ed.), Energy, carbon and othermaterial flows in the life cycle assessment of forestry and forest products — achievements of the working group 1 of the COST action E9. European Forest Institute (EFI), Joensuu, Finland.

Sjølie, H.K., 2011. Analyses of the use of the Norwegian forest sector in climate change mitigation. Department of Ecology and Natural Resource Management, PhD thesis, Ås, Norwegian University of Life Sciences.

Smeets, E., Faaij, A., 2007. Bioenergy potentials from forestry in 2050. Climatic Change 81 (3), 353-90.

Smith, S.J., Wigley, M.L., 2000. Global Warming Potentials: 1. Climatic Implications of Emissions Reductions. Climatic Change 44 (4), 445-57.

Sonne, E., 2006. Greenhouse Gas Emissions from Forestry Operations. Journal of Environvironmental Quality 35 (4), 1439-50.

SSB, 2011a. Forestry. Statistics Norway: http://www.ssb.no/skog_en/ Visited on September 2011.

SSB, 2011b. Energy. Statistics Norway: http://www.ssb.no/english/subjects/01/03/10/energi_en/ Visited on September 2011.

SSB, 2011c. Forest properties' average productive forest area, by county. 2009. Decares. Statistics Norway: http://www.ssb.no/english/subjects/10/04/20/stskog_en/ Visited on September 2011.

SSB, 2011d. Emissions of greenhouse gases. 1990-2010, preliminary figures. Statistics Norway: Visited on September 2011.

Tahvanainen, T., Anttila, P., 2011. Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass and Bioenergy 35 (8), 3360-75.

Thornley, P., Upham, P., Tomei, J., 2009. Sustainability constraints on UK bioenergy development. Energy Policy 37 (12), 5623-35.

UN, 1992. United Nations Conference on Environment and Development. Rio de Janeiro, 3-14 June 1992 www.unep.org Visited on September 2011.

UN, 1998. Kyoto Protocol to the United Nations framework convention on climate change.

Van Belle, J.-F., Temmerman, M., Schenkel, Y., 2003. Three level procurement of forest residues for power plant. Biomass and Bioenergy 24 (4-5), 401-9.

WCED, 1987. Our common future. World Commission on Environment and Development, Oxford, Oxford University Press.

Wessman, H., Alvarado, F., Backlund, B., Berg, S., Hohenthal, C., Kaila, S., Lindholm, E-L., 2003. Land use in ecobalance and LCA of forest products. SCAN-Forsk rapport 746, Stockholm, Sweden.

Wihersaari, M., 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28, 435–43.

Zainal, Z., 2007. Case study as a research method. Jurnal Kemanusiaan 9, 1-6.

APPENDIX

This appendix specifies the main input data assumptions for papers 1, 2 and 3, which are not explicitly presented in those papers.

Table A1: Main input data assumptions for paper 1

Variable	*Assumptions*
Average standing volume of the total surface of forest stands extracted	41.6 m^3/ha
Maximum standing volume allowed to extract	70%
Total stemwood volume distribution:	13474 m^3
Norway spruce	60%
Scots Pine	30%
Birch	10%
a_i, b_i parameter for each tree species	Same as Lehtonen et al. (2004)
Energy content (diesel)	36.22 MJ/l
Maximum load of truck	50 tons
Model slash bundler	Timberjack 1490D
Bundles characteristics	70–75 cm diameter, cut by a chain saw into 3 m length
Emission factors used for all machineries	CO_2: 3.17 kg/t; N_20: 0.12555 kg/t; CH_4: 0.09688 kg/t
Terminal definition	Transportation of bundles and stemwood to the terminal

Table A2: Main input data assumptions for paper 2

Variable	*Assumptions*
Storage time for wood chips	Less than 1 year
Fuel consumption from personal communication	Compared to literature source: train: NSB (2010) and NSB (2011) chipping: Van Belle (2006) based on Liss (1987) loading: Hansson et al.(2003) truck: González-García et al. (2009) and Michelsen et al. (2008)
Emission value for CH_4 and N_20 at CHP plant	Same as Wihersaari (2005) based on Harju (2001): N_2O: < 1 mg/MJ wood chip CH_4: 0.4-0.8 mg/MJ wood chip

Table A3: Main input data assumptions for paper 3

Variable	*Assumptions*
Efficiency of biomass, natural gas and fuel oil plant	85%
Emission coefficients for natural gas and fuel oil (kg CO_{2e})	Fuel oil (light fuel oil): 2.5442 kgCO_{2e} per unit Natural gas: 2.0133 kgCO_{2e} per unit Emissions from extraction, refinery and transportation excluded
Total volume of wood chips at DHP	90% from saw mill residues, produced in the local saw mill of Cavalese and 10% from mountain forests
Conversion factor and energy equivalence	Same as Hellrigl (2006)
Moisture content of woody biomass (both round wood and logging residues)	Same as Spinelli et al. (2008)
Wood chip characteristics from logging residues	Density: 287 kg/loose m^3 or 393 kg/m^3 s.o.b. (dry), source: Spinelli et al. (2006) Energy content: 0.72 MWh/loose m^3 tree species: Norway spruce
Loading capacity of truck	38 loose m^3, source: Spinelli et al. (2006)
Density of fuel for all machineries included chainsaw (kg/l)	Source: OECD/IEA (2005)
Emission factors expressed for fuel type (kg/TJ diesel)	Source: IPCC (2006)
NCV (Tj/Gg)	Source: IPCC (2006)
Woody biomass volume for WST and SWS	Same volume
Energy input-output ratio	Calculation are referred only to logging residues, not total woody biomass
Heating value of wood chips at biomass plant	2 MWh/m^3 s.o.b.
Light fuel oil characteristics	NCV: 42.5 MJ/kg Density: 0.85 kg/l, source: AEIL (2009)
Natural gas characteristics	NCV: 56.1 MJ/kg Density: 0.719 kg/m^3, source: Hellrigl (2001)
Emissions from fuel oil plant	2300 ton CO_{2e}
Emissions from biomass combustion	Emissions included only in the GHG balance (figure 3)
Emissions from natural gas plant	1700 ton CO_{2e}
Fuel storage of wood chip at DHP	Excluded by calculation

APPENDIX REFERENCES

AIEL, 2009. Legna e cippato. Produzione, requisiti e compravendita Associazione Italiana Energie Agroforestali, Legnaro, Italy.

González-García, S., Berg, S., Feijoo, G., Moreira, M., 2009. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. The International Journal of Life Cycle Assessment 14 (4), 340-53.

Hansson, P.-A., Dahlin, B., Blinge, M., 2003. Air emissions from the fuel supply system of a Swedish CHP plant and the effects of stricter emission regulations. Biomass and Bioenergy 24 (1), 59-68.

Harju, T., 2001. Puuenergiapolton materiaalivirrat (Material streams of wood fuel combustion). Osahankkeen loppuraportti Tekesin Puuenergian teknologiaohjelmassa VTT Kemiantekniikka.

Hellrigl, B., 2001. Numeri per la Dendroenergetica. Edizione provvisoria, Milano.

Hellrigl, B., 2006. Elementi di xiloenergetica (Elements of wood energy). Associazione Italiana Energie Agroforestali., Legnaro, Italy.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. Introduction. Intergovernmental Panel of Climate Change, Japan.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management 188 (1-3), 211-24.

Liss, J., 1987. Effektbehov och energiförbrukning vid produktion av bränsleflis med lantbrukstraktormonterade huggar (power requirement and energy consumption in fuel-chip production using a tractor-mounted chipper). Sveriges Lantbruksuniversitet, Garpenberg: Sweden, pp.88.

Michelsen, O., Solli, C., Strømman, A.-H., 2008. Environmental Impact and Added Value in Forestry Operations in Norway. Journal of Industrial Ecology 12 (1), 69-81.

NSB, 2010. Miljøregnskap NSB Konsern 2010, Norway, 1-29.

NSB, 2011. Railway operations and energy consumption, Report, Norway.

OECD/IEA, 2005. Energy Statistics Manual. International Energy Agency, Paris, 81.

Spinelli, R., Nati, C., Magagnotti, N., 2006. Recupero di biomassa: alcune utilizzazioni in boschi alpini. Sherwood 119, 1-7.

Spinelli, R., Magagnotti, N., Dellagiacoma, F., 2008. Meccanizzazione nelle fustaie alpine. Due diversi sistemi di lavoro Sherwood 147, 45-9.

Van Belle, J.-F., 2006. A model to estimate fossil CO2 emissions during the harvesting of forest residues for energy with an application on the case of chipping. Biomass and Bioenergy 30 (12), 1067-75.

Wihersaari, M., 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28, 435–43.

Paper 1

Scandinavian Journal of Forest Research, 2011; 26: 429–436

ORIGINAL ARTICLE

Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain

CLARA VALENTE[1,2], BENGT GUNNAR HILLRING[1] & BIRGER SOLBERG[2]

[1]*Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, NO-2480 Koppang, Norway, and* [2]*Department of Ecology and Natural resource Management, Norwegian University of Life Sciences, P.O. BOX. 5003, NO-1432, Ås, Norway*

Abstract
Norwegian mountain forests represent interesting sources of wood biomass for bioenergy. This case study gives a life cycle assessment of the greenhouse gas (GHG) emissions and costs of forest management, harvest and transport operations in the mountainous areas of Hedmark and Oppland counties in Norway. Low-intensity forest management characterizes the study sites. The study shows that transportation to the terminal is the operation with the highest GHG impacts in the examined supply chain and that the bundling of forest residues has the highest financial cost. The mountain forest system analyzed emits 17,600 g CO_2e per solid cubic meter over bark. Transportation to the terminal accounts for 31% of the emissions and 23% of the costs, while bundling accounts for 25% of the total emissions and 19% of the total costs. The study shows that there is a considerable quantity of woody biomass available for bioenergy purpose from mountain areas. In the short term, it is possible to integrate harvesting of logging residues in the conventional logging operations. However, it is necessary to improve forest management, logistic and technology for reducing emissions and operative costs, ensuring the achievement of a sustainable system at the same time.

Keywords: *Forest system, greenhouse gas emissions, life cycle assessment, mountainous areas, Norway.*

Introduction

During recent years, the use of wood for bioenergy purpose has become an interesting alternative to fossil fuels (Eriksson et al., 2002; Raymer, 2006). Concerns about climate change and a considerable growth in the greenhouse gas (GHG) emissions have encouraged several countries to introduce appropriate policies for mitigating global warming and at the same time find further sites of extraction of raw materials, such as forests in the mountain areas. The Norwegian Parliament has instituted a climate change adaptation program for preventing and reducing the consequences of climate change (Norwegian Parliament, 2009).

Mountain forests cover 28% of the total world's forests. At the global scale, mountain forests are main source of freshwater and play a key role in the supply of timber, fuel wood and non-wood products for both mountain and lowland populations (Butt & Price, 2000). One-tenth of the total human population lives in mountain regions, where around 90% of the total energy consumption is provided by wood biomass (Price & Butt, 2000). Compared to lowland forests, mountain areas are characterized by different species composition, greater changes in climatic conditions, slower forest dynamics, regeneration and growth. In addition, low intensity and high costs of forest operations and few job opportunities typify mountain areas (Price, 2003).

In Norway, 30% of the total forest land is classified as mountain forests (Hannerz, 2003), defined as forests bordering mountain areas, where at least 50% of the forests should preserve a mature character (LMD, 2005). Specific rules and environmental restrictions characterize the management of these Norwegian forest stands. Selective cutting and small-scale clear cutting or group cutting, clear cutting of areas from 0.2 to 0.5 ha, are the conventional harvesting systems for mountain conditions. The harvest extracts only part of the standing

Correspondence: Clara Valente, Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, Anne Evenstadsvei 80, 2480 Koppang, Norway. E-mail: clara.valente@hihm.no

(*Received 2 November 2010; accepted 8 March 2011*)

ISSN 0282-7581 print/ISSN 1651-1891 online
DOI: 10.1080/02827581.2011.570783

volume and uneven aged forest structure should be maintained over time (Lexerød & Eid, 2006). Difficult terrain and possible negative effects on this sensitive environment and value of the forest make forest operations in mountainous conditions challenging (Heinimann, 2004). The Norwegian forest certification standard (Levende Skog, 2006) focuses the attention on the sustainability of forest management, including the safeguard of biodiversity both at species and landscape levels and the recreational values of mountain forests. Few endemic species characterize Scandinavian mountains and mountain-dwelling organisms live in marginal areas compared to their whole distribution (Ministry of Environment, 2003). However, it is important to ensure the protection of biodiversity in this environment.

In Norway, mountain forests are sites historically used for several purposes. Summer farming *seterdrifta* was typical of this landscape. The prediction of higher temperatures, longer growing seasons and the shift of the timberline due to climate change may lead to the development of more commercial forestry at higher altitude (Grace et al., 2002). The natural regeneration of forest stands on abandoned pastures is an additional reason for enlargement of the productive forests in the mountains. Hence, large amount of woody biomass from these areas might be available for the harvest of bioenergy. Increased forest operations and greater exploitation of mountain regions have advantages and disadvantages, which have to be weighed up. The use of woody biomass from mountain forests might be justified by the reduction of CO_2 emissions in the atmosphere, thanks to the replacement of fossil fuels by forest bioenergy and the revitalization of mountainous areas for socio-economical reasons.

There is a strong need to improve the knowledge relating to mountain forest system in order to identify the factors for and against utilizing woody biomass from mountainous forest stands for energy. The main objective of this article is to perform a life cycle assessment (LCA), including an economical analysis, of forest management and operations in mountainous sites through the evaluation of a case study in the Norwegian counties of Hedmark and Oppland. To our knowledge, no LCA studies in mountain forests have been carried out before, and the integration of the economic dimension is rather rare in an LCA context.

A life cycle inventory (LCI) regarding the use of raw material, primary energy and fossil fuel is carried out. GHG emissions and costs are calculated for each part of the considered system and the most important processes are identified.

Materials and methods

The study was performed in the Norwegian counties of Hedmark and Oppland (Figure 1), where around 35% of the total forested area is covered by mountain forests. In the years 2008 and 2009, 31 mountainous forest stands were selected for the investigation, based on two criteria: the harvest should be a maximum of 70% of the total standing volume and their location should be between 700 and 1000 m a.s.l. At this altitude, climatic conditions limit tree growth, regeneration and productivity (Heje & Nygaard, 1998; Moen, 1999) and the rotation period is around 150 years, significantly longer than in lower altitude boreal forests. Above this altitude, the forests are protected because they are considered areas of particular environmental value. These forests are more vulnerable and sensitive to changes and hence it is necessary to request special permission for logging operations. The surface of all 31 stands was 324 ha. Norway spruce [*Picea abies* (L.) Karst.] and Scots pine [*Pinus sylvestris* L.] were the dominant tree species.

The methodology used was LCA, an international standardized technique used for evaluating the environmental impacts of a product, process or service (ISO, 2006a, 2000b).

In the current study, an LCA of the wood supply chain was performed from *cradle to gate*, i.e. from the extraction of raw materials in the specific mountain forests to the delivery at the processing terminal. Both the use and disposal phase of the product were omitted. The impacts regarding GHG emissions and economic costs were assessed for each stage of the chain from silviculture to the transport to the terminal, including regeneration, logging operations and road transportation.

The study system boundary is the mountain forest fuel system, as shown in Figure 2. The system describes the woody biomass supply chain, a network of forest management and the operations involved in the wood production from the stands to the delivery of woody biomass at the terminal. The woody biomass consists of stemwood and logging residues. The forest management integrated in the forest operations comprises two silviculture operations: soil scarification for improving the forest growth rate and regeneration, i.e. planting replacement trees. Felling and terrain transport were done using harvesters and constitute the intermediate parts of the supply chain. In mountain areas, the forest residues are generally left at the stands, but in our case residues were bundled and removed. Bundling or production of compact residue logs through a slash bundler mounted on a standard forwarder

Figure 1. Locations of Hedmark and Oppland counties in Norway.

represents an extension of the system boundary. The bundles were transported to the terminal by a conventional timber truck. The logging residues consist of above-ground tree parts as branches, tops and foliage left at the site from the harvesting operations. Stumps and roots were left at the forest stand.

The functional unit in the LCA is the equivalent of 1 solid cubic meter of woody biomass over bark (1 m^3 s.o.b.) delivered to the terminal. The use of

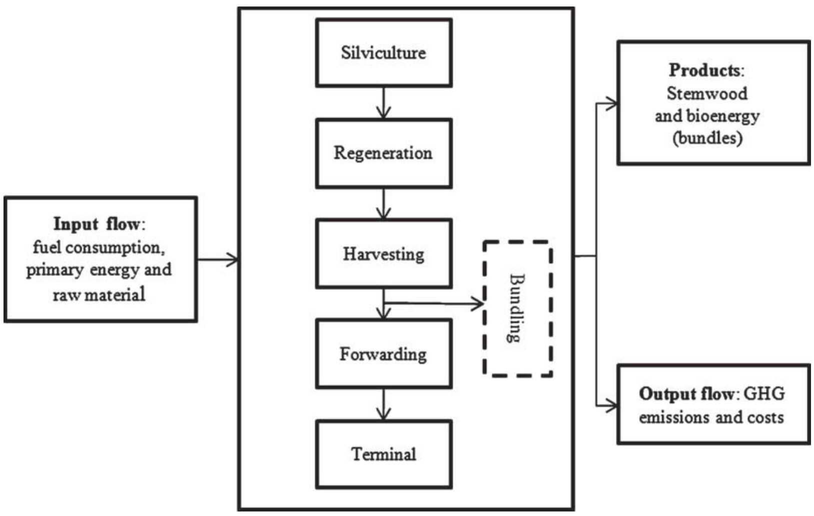


Figure 2. System boundary of the mountain forest fuel system: main unit processes and flows involved in the life cycle assessment. Dotted line: expansion of the system boundary.

raw materials (m^3 s.o.b.), primary energy (MJ/m^3 s.o.b.) defined as energy input, fuel consumption (l/m^3 s.o.b.), GHG emissions (g CO_2e/m^3 s.o.b.) and costs (NOK/m^3 s.o.b.) were all referred to by this unit. The calculation of the emissions are related to climate change impact category as used by IPCC (2006). The characterization model used is the potential global warming with a time horizon of 100 years (GWP_{100}) for the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

An appropriate allocation procedure was suggested for assessing the environmental and economic performance of the mountain forest that produces two different products: stemwood and bioenergy. The allocation was made by the assumption of the physical causality approach, such as mass of the outputs, as suggested by the ISO standard. At the end, a sensitivity check was performed for assessing the reliability of the final results and identifying the processes of the supply chain with the highest impacts in terms of emissions and costs.

Primary data were collected from our own fieldwork and secondary data taken from literature sources (Table I). Their quality varied. Low intensity of logging operations in Hedmark and Oppland mountain forests and our preference to use local data sources made the data collection rather challenging. The current level of silviculture and regeneration, not conventional in Norwegian mountain forests, was assumed to be allocated to the current level of logging. The fuel consumption was assumed 10% higher than in lowland forest operations. Planting was assumed as conventional silvicultural management of the forested stand. The forwarding distance was assumed to be 1200 m, while the average transportation distance from landing to the terminal was assumed to be 64 km with 46% as load factor, i.e. the distance driven with a full load timber truck per round trip. Subsidies and costs of road construction were not included in the study.

Table I. Data collection and sources

Data	Source
Forest stands: harvesting volume[a,b], altitude[a,b], location[a,b], general characteristics of the stand[c] (vegetation type[d], tree composition[d], productivity[e], quality[e])	[a]Forestry company: Mjøsen Skog; T. Wangen (personal communication, 2010) [b]Hedmark municipality: Fylkesmannen i Hedmark; T. Kringlebotn and M. Sandtrøen (personal communication, 2010) [c]Field work [d]Moen (1999) [e]Heje and Nygaard (1998)
Silviculture[f,g,h]	Literature: [f]Kringlebotn et al. (2010); [g]Flæte (2009)
Regeneration[a,b,g]	See a, b and g above
Harvesting and forwarding[a,b,g,h,i]	See a, b, g above and [h] Forstkandidat Myrbakken Ltd; S. Myrbakken (personal communication, 2010); [i]Glommen Skog BA (2008)
Terminal[g]	See g above
Emissions factors[j]	[j]Sandmo (2009)

The amount of logging residues as branches and foliage was estimated through the biomass functions of Lehtonen et al. (2004) by the following equation:

$$W_i(V) = a_i V b_i$$

where $W_i(V)$ is the total biomass calculated in ton dry matter (ton d.m./ha) for each tree parts i, a_i and b_i are parameters, i is the biomass component (branches and foliage) and V is the stem volume (m^3/ha). According to the experience, tops were assumed to be 10% of the stem biomass, including bark. Based on Hakkila (2003) it was assumed that 30% of the forest residues were left on the ground for ecological reasons.

Finally, based on the physical causality approach it was assumed that 70% of the overall emissions and costs were allocated to stemwood production and 30% to bioenergy production. In the sensitivity check, each unit process in the LCA was decreased and increased by 10%, one at a time. The goal was to find out the change in the result larger or smaller than 1.5% compared to the final results.

Results

The results of the life cycle inventory are summarized in Table II. The total volume of woody biomass harvested was 18,251 m^3 s.o.b.: 13,474 m^3 s.o.b. stemwood and 4777 m^3 s.o.b. logging residues. The processes with the highest and lowest total fuel consumption and primary energy use were transportation to the terminal and silviculture, respectively. The emissions of CO_2, N_2O and CH_4

Table II. Input of raw material, fuel consumption and primary energy for each unit process

	Raw material	Fuel consumption		Primary energy	
	m^3 s.o.b.	l/m^3 s.o.b.	l	MJ/m^3 s.o.b.	MJ
Silviculture	18,251	0.02	309	0.61	11,192
Regeneration	18,251	0.08	1545	3.07	55,960
Harvesting	18,251	1.13	20,578	40.81	744,924
Forwarding	18,251	1.57	28,708	56.94	1,039,259
Bundling[a]	4777	1.65	7882	59.73	285,330
Terminal	18,251	2.06	37,542	74.46	1,359,032

Note: [a]Only logging residues volume.

Table III. Estimated emissions of CO_2, N_2O, CH_4 (g/m^3 s.o.b.)

	CO_2	N_2O	CH_4
Silviculture	45.11	0.002	0.001
Regeneration	225.54	0.009	0.007
Harvesting	3002.89	0.12	0.09
Forwarding	4188.58	0.17	0.13
Bundling	4393.62	0.17	0.13
Terminal	4832.98	0.22	0.17
Total	16688.7	0.691	0.528
Rounded off	16700	0.691	0.53

were particularly high for bundling because of the small amount of logging residues (Table III).

The results of GWP_{100} (g CO2e/m^3 s.o.b.) and costs (NOK/m^3 s.o.b.) are illustrated in Figure 3. The mountain forest system analyzed had an overall output of 17,600 g CO_2e/m^3 s.o.b., assuming a GWP_{100} of 298 and 25, respectively, for N_2O and CH_4. The process with the highest share of emissions, 31%, was transportation to the terminal. Harvesting, forwarding and transportation to the terminal caused around 73% of the total g CO_2e/m^3 s.o.b., mainly because of the use of fossil fuels. The impacts of both silviculture and regeneration reflected only 2% of the total emissions. The costs were homogeneously distributed in the system. The total costs were 463 NOK/m^3 s.o.b. Harvesting, forwarding and transportation to the terminal accounted for 56% of the total costs. Regeneration (planting) was costly (17% of the total costs), while silviculture (soil scarification) represented 8% of the total costs. The bundling process had high impact concerning emissions, 4449 g CO_2e/m^3 s.o.b. that represented 25% of the total emissions and costs 88 NOK/m^3 s.o.b. or 19% of the total costs.

The variation of both emissions and costs between the analyzed 31 stands was also taken into account. However, it proved to be insignificant because of similar conditions between sites.

The results of the sensitivity check concerning the results were shown in Table IV. A decrease of 10% in the transportation to the terminal gave 2.2% less emissions. An increment of 10% in bundling gave 1.8% more emissions. Regarding the costs, the most sensitive parameters were transportation to the terminal followed by bundling.

In later analyses, it might be useful to allocate the emissions and costs in relation to different assortments. Our estimation shows that 12,300 g CO_2e/m^3 s.o.b. of the emissions and 324 NOK/m^3 s.o.b. of the costs might be allocated to stemwood production while 5265 g CO_2e/m^3 s.o.b. and 139 NOK/m^3 s.o.b. to bioenergy production.

Discussion

This study supports the idea that wood biomass from mountain areas would be an interesting raw material for bioenergy in the long term if there will be more pressure on both local and international markets. The results show that there is a great unused potential of stemwood as well as logging residues in the mountain forests of Hedmark and Oppland counties, confirmed by the scarcity of forestry activities in these areas.

Very few previous studies exist on the studied topic for mountain areas, where the attention has mainly been on specific forestry operations in alpine context. For example, Spinelli and Magagnotti (2009) studied the use of a truck-mounted bundler under mountainous conditions, finding similar performance to the forwarder-mounted bundler used

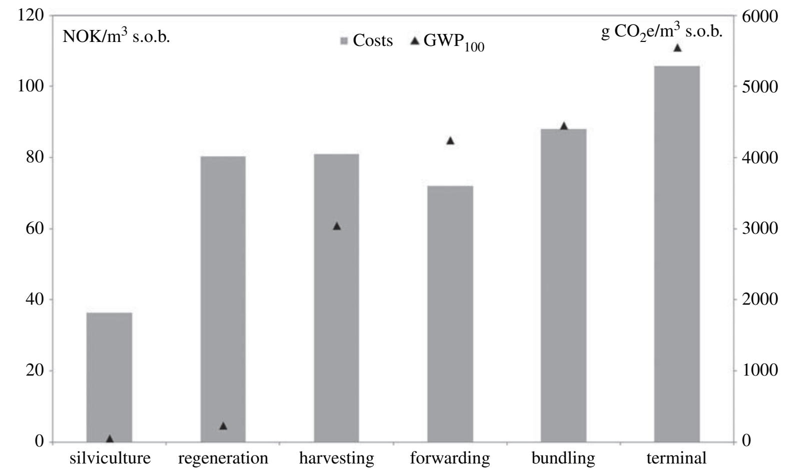


Figure 3. Characterization results for climate change GWP_{100} (g CO_2e/m^3 s.o.b.) and costs (NOK/m^3 s.o.b.). Total emissions 17,600 g CO_2e/m^3 s.o.b., and total costs 463 NOK/m^3 s.o.b. Note: 8 NOK = 1 euro.

Table IV. Sensitivity check of the final results related to GHG emissions and costs: reduction (− 10%) and increment (+ 10%) of each unit process

	GHG emissions		Costs	
	−10%	+10%	−10%	+10%
Silviculture	−0.03	0.02	−0.73	0.72
Regeneration	−0.13	0.13	−1.46	1.41
Harvesting	−1.46	1.41	−1.47	1.42
Forwarding	−1.88	1.79	−1.33	1.29
Bundling	−1.94	1.84	−1.57	1.51
Terminal	−2.23	2.09	−1.74	1.72

in Scandinavia. Stampfer and Kanzian (2006) analyzed the wood chip supply chain in Austrian mountain areas. Their results showed that a proper separation of chipping and transportation reduces the costs by 24–32%. Instead, studies conducted in lowland conditions were related to energy use and GHG emissions from forest operations. Examples of these studies come from Sweden and Finland, i.e. Karjalainen and Asikainen (1996), Berg and Karjalainen (2003) and Berg and Lindholm (2005). Schwaiger and Zimmer (2001) calculate GHG emissions and fuel consumption for Europe. In Norway, Michelsen et al. (2008) performed a hybrid LCA where emissions and costs were presented. In the present study, the costs of harvesting and forwarding were found to be 31 NOK/m^3 higher. Nevertheless, differences in data collected, studied areas, functional units, unit process included and assumptions made contribute to the variation between results. All studies as well as the present one identify transportation as the weakest point in the supply chain in terms of emissions. The sensitivity check confirms this point. The explanation is mainly due to high fossil fuel consumption and long transportation distance from the forest stand to the terminal. In all these studies, with the exception of Lindholm (2010), the woody biomass is not harvested for bioenergy purpose and logging residues are left at the forest stands. Under mountainous conditions, the harvesting of logging residues has negative environmental impacts and high costs because of the introduction of extra machinery into the system (the bundler) and the scarcity of raw materials. Nevertheless, studies from Southern Europe such as Kanzian (2006) and Spinelli and Magagnotti (2009) concerning forestry mechanization suggest that from a technical point of view there is a great potential in the use of logging residues as biofuel from mountain forests. A reduction of fossil fuel consumption and more efficient logistics can give benefits in terms of GHG emissions and costs. In mountain areas, bundling is considered a good method for handling logging residues (Stampfer & Kanzian, 2006) and is clearly advantageous in case of long transportation distance (Kärhä & Vartiamäki, 2006). The advantages of bundling are visible when the whole supply chain is taken into consideration and managed correctly (Kilponen, 2010).

In general, low intensity of forest management characterizes Norwegian forests, especially in mountain areas. It is hard to find seeds adapted to mountain conditions and soil scarification is rare. Therefore, at the moment the costs of silviculture and regeneration are high. However, the implementation of forest management as soil scarification and planting can improve the quality of mountain forests, which today is really poor and thus in the long term generate more wood for bioenergy purpose.

The current LCA covers only part of the total carbon budget and a more complete analysis should include a carbon balance of the mountain forest ecosystem. According to Cherubini (2010), each bioenergy system should increase the carbon stock for maximizing the GHG saving.

We split up the wood value chain excluding the conversion of wood to energy. This will be assessed in future studies using the results from this study and assuming that forest fuel will substitute fossil fuel.

The introduction of technologies that are more efficient – combined machinery and simultaneous harvesting of stemwood and logging residues – seem promising in terms of emissions and costs. For example, more efficient slash bundlers (John Deere, 2010), truck-mounted bundlers (Lindroos et al., 2010) and farm tractors with a grapple loader trailer for hauling logging residues and soil scarification (Gullberg & Johansson, 2006) allow the integration of several operations at the same time and consequentially reduce emissions and costs.

Regarding the methodology, the LCA is an established tool designed to assess a product in quantitative terms through the use of a functional unit. Nevertheless, some authors such as Finnveden (2000) highlights lacks in the methodology, in particular the disregard on specific sites condition and emissions over time. In addition, over the years the issues and scopes of the LCA are changed. Environmental impacts as biodiversity, land use change and soil quality have been included in the LCA, although often rather difficult to evaluate.

The integration of wood biofuels in all phases of the supply chain is a key element to reduce operating costs and increase the efficiency of the mountainous forest fuel system. Only in this way, is it feasible to use energy sources located in remote areas. One main challenge is to develop a stable bioenergy market and identify the technologies best adapted to mountainous forest stands. Forest management, bundling and transportation are key points to improve in mountain forests. Easier access to raw materials and a correct and sustainable utilization of mountain forests is easily achievable. Moreover, it is important to ensure the respect of other environmental impacts than GHG emissions as biodiversity.

Further analyses are necessary for assessing the impacts of bioenergy production from the terminal to the end users.

Acknowledgements

The authors gratefully acknowledge the support for data collection of Mjøsen SB Skog, Fylkesmannen i Hedmark and Forstkandidat Myrbakken Ltd. We also thank Jos Milner, for English revision.

References

Berg, S. & Karjalainen, T. (2003). Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. *Forestry*, *76*(*3*), 271–284.

Berg, S. & Lindholm, E.-L. (2005). Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production*, *13*(*1*), 33–42.

Butt, N. & Price, M. F. (Eds) (2000). Mountain people, forests and trees: Strategies for balancing local management and outside interests. *Synthesis of an Electronic Conference of the Mountain Forum*, April 12–May 14, 1999, Franklin, West Virginia.

Cherubini, F. (2010). GHG balances of bioenergy systems – Overview of key steps in the production chain and methodological concerns. *Renewable Energy*, *35*(*7*), 1–9.

Eriksson, H., Hall, J. & Helynen, S. (2002). Rationale for forest energy production. In: J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice, pp. 1–17,* The Netherlands: Kluwer Academic Publishers.

Finnveden, G. (2000). On the limitations of life cycle assessment and environmental systems analysis tools in general. *The International Journal of Life Cycle Assessment*, *5*(*4*), 229–238.

Flæte, P. O. (2009). *Energiforbruk og utslipp fra skogproduksjonskjeden med utgangspunkt i aktivitetsdata fra 2007- fra frø til industritomt* [Energy consumption and emissions from forest production chain based on activity data from 2007 – from seed to timber industry], Working paper. Ås: Norsk institutt for skog og landskap (in Norwegian).

Glommen Skog, B.A. (2008). *Prisliste for hogst og kjoring maskinell sluttavvirking Trysil, Rendalen og Stor-Elvdal. Imsdalen Vedlegg til rapport driftskostnader og tømmerpris* [Price list for cutting and driving forest machinaries in Trysil, Rendalen and Stor-Elvdal. Imsdalen Appendix to report operating costs and timber prices] Internal Report. Norway: Nord-Østerdal (in Norwegian).

Grace, J., Berninger, F. & Nagy, L. (2002). Impacts of climate change on the tree line. *Annals of Botany*, *90*(*4*), 537–544.

Gullberg, T. & Johansson, J. (2006). A method for integrated extraction of logging residues and soil scarification on a small scale. *Biomass and Bioenergy*, *30*, 1035–1042.

Hakkila, P. (2003). *Developing technology for large-scale production of forest chips: Wood energy technology programme 1999–2003. Interim Report*. Helsinki: National Technology Agency.

Hannerz, M. (2003). Forest research in the north. News & Views No. 4. *Scandinavian Journal of Forest Research*, *18*, 291–293.

Heinimann, H. R. (2004). Harvesting | Forest operations under mountainous conditions. In: J. Burley, J. Evans & J. Youngquist (Eds.), *Encyclopedia of forest sciences,* pp. 279–285, Oxford: Elsevier Academic Press.

Heje, K. K. & Nygaard, J. (1998). *Norsk skoghåndbok* [Forestry handbook]. Oslo: Landbruksforlaget (in Norwegian).

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. In: H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (Eds.), Japan: IGES Publisher.

ISO (2006a). *ISO 14040: 2006. Environmental management – Life cycle assessment –Principles and framework*. Geneva, Switzerland: International Organization for Standardization.

ISO (2006b). *ISO 14044: 2006. Environmental management – Life cycle assessment –Principles and framework*. Geneva, Switzerland: International Organization for Standardization.

John Deere (2010). *Product Program 2010. Forest machines*. Märsta: Sweden.

Kanzian, C. (2006). Logging redidues as biofuel – Case studies of supply chains under mountainous conditions. In: Seminar Proceedings, 40 [Poster], *RecAsh 2nd International Seminar*, September 26–27 (28), 2006, Karlstad, The Swedish Forest Agency.

Karjalainen, T. & Asikainen, A. (1996). Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. *Forestry*, *69*(*3*), 215–228.

Kärhä, K. & Vartiamäki, T. (2006). Productivity and costs of slash bundling in Nordic conditions. *Biomass and Bioenergy*, *30*(*12*), 1043–1052.

Kilponen, M. (2010). 10 years with slash bundles – More efficiency and flexibility to forest energy logistics. In: FINBIO (Ed.), *Forest Bioenergy 2010 from 31st August– 4th September 2010. Book of Proceedings*, Vol. 47, pp. 129–134 Jyväskylä, Finland: FINBIO.

Kringlebotn, T., Haget, D., Nyberget, A–L. O., Skyrud, R. E., Kjær, R., Sandtrøen, M., Holaker, T., Sæhlie, O. & Sandberg, E. (2010). *Hedmarksskogbruket i tall, Skogfondregnskapet 2009 og skogstatistikk 2009* [Hedmark Forestry in figures, Forest Trust Fund accounts 2009 and forestry statistic 2009]. Rapport 01/10, 42 sider, pp. 1–43, Hamar, Norway: Fylkesmannen i Hedmark, Landbruksavdelingen (in Norwegian).

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R. & Liski, J. (2004). Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *Forest Ecology and Management*, *188*(*1–3*), 211–224.

Levende Skog (2006). *Living forest: Standard for sustainable forest management in Norway*, pp. 1–40. Oslo, Norway: Levende Skog.

Lexerød, N. L. & Eid, T. (2006). Assessing suitability for selective cutting using a stand level index. *Forest Ecology and Management*, *237*(*1–3*), 503–512.

Lindholm, E.-L. (2010). *Energy use and environmental impact of roundwood and forest fuel production in Sweden*. Doctoral dissertation, Swedish University of Agricultural Sciences, 2010. *Acta Universitatis Agriculturae Sueciae*, 40.

Lindroos, O., Matisons, M., Johansson, P. & Nordfjell, T. (2010). Productivity of a prototype truck-mounted logging residue bundler and a road-side bundling system. *Silva Fennica*, *44*(*3*), 547–559.

LMD (2005). Lov 2005-05-27 nr 31: Lov om skogbruk (skogbrukslova); Act of 2005-05-27 nr 31; *Act on forestry (forestry act)*. Oslo: The Norwegian Ministry of Agriculture and Food.

Michelsen, O., Solli, C. & Strømman, A. H. (2008). Environmental impact and added value in forestry operations in Norway. *Journal of Industrial Ecology*, *12*, 69–81.

Ministry of Environment (2003). Thematic Report on Mountain Ecosystems – Norway. Convention on Biological Diversity. Retrieved September 10, 2010, from http://www.cbd.int/reports/search/?type = nr-me

Moen, A. (Ed.) (1999). *National atlas of Norway: vegetation*. Hønefoss: Norwegian Map Authority.

Norwegian Parliament (2009). Klima, energi, landbruk og mat – internasjonale og nasjonale rammer og utfordringer [Climate change, energy, agriculture and food-international and national frameworks and challenges]. In: *Klimautfordringene –landbruket en del av løsningen* [Climate change-agriculture part of the solution]. *Stortingsmelding nr. 39 (2008–2009)*, Landbruks og matdepartment [Agriculture and Food Department] (in Norwegian).

Price, M. F. (2003). Why mountain forests are important? *The Forestry Chronicle*, *79*(*2*), 219–222.

Price, M. F. & Butt, N. (Eds.) (2000). *Forests in sustainable mountain development: A state-of-knowledge report for 2000*. Wallingford: CABI.

Raymer, A. K. P. (2006). A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy*, *30*, 605–617.

Sandmo, T. (Ed.) (2009). *The Norwegian Emission Inventory 2009. Documentation of Methodologies for Estimating Emissions of Greenhouse Gases and Long-Range Transboundary Air Pollutants*. Norway: Statistics Norway, Department of Economics, Energy and the Environment Statistics.

Schwaiger, H. & Zimmer, B. (2001). A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. In: T. Karjalainen, B. Zimmer, S. Berg, J. Welling, H. Schwaiger, L. Finér & P. Cortijo (Eds), *Energy, carbon and other material flows in the life cycle assessment of forestry and forest products,* Discussion Paper 10. Joensuu, Finland: European Forest Institute.

Spinelli, R. & Magagnotti, N. (2009). Logging residue bundling at the roadside in mountain operations. *Scandinavian Journal of Forest Research*, *24*(*2*), 173–181.

Stampfer, K. & Kanzian, C. (2006). Current state and development possibilities of wood chip supply chain in Austria. *Croatian Journal of Forest Engineering*, *27*(*2*), 135–145.

Paper 2

Greenhouse Gas Emissions, Energy Use and Costs of Wood Fuel Supply Chains in Scandinavia

Abstract Use of bioenergy based on woody biomass has become increasingly important in recent years, especially in European countries. In three case studies from Scandinavia, we conducted life-cycle assessment (LCA) of different alternatives of wood fuel supply chains (WFSCs) according to greenhouse gas (GHG) emissions, energy use and costs. GHGs and energy use were lower when wood chips are exported from Norway to Sweden. From a GHG point of view, WFSCs, with relatively long transport distances were best when transportation was by railway and the combustion plant had high efficiency. The highest production of GHGs was transportation by truck and chipping operations. Forest fuels from mountain forests were a good choice for filling the high demand for wood fuel in Sweden, where bioenergy use is relatively high. In all case studies, the GHG balance was positive, especially when wood fuel plant substituted energy production from coal and oil plants. The cost analysis showed importation of wood chips from Norway was economically feasible.

Keywords: bioenergy, LCA, mountain forests, Norway, Sweden.

Authors information:

Clara Valente [a,b], Bengt Gunnar Hillring [a] Birger Solberg [b]

a Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, NO-2480, Koppang, Norway

b Department of Ecology and Natural resource Management, Norwegian University of Life Sciences, P.O. BOX. 5003, NO-1432, Ås, Norway

Introduction

The necessity to substitute fossil fuels to preserve the environment and mitigate global warming has been a key factor for the implementation of renewable energy. An EU directive has set the target to contribute 20% energy share through renewable energy sources by 2020 (European Parliament 2009). In a European context, the development of energy production based on renewable sources has been a key element of a sustainable future. The use of woody biomass for energy production could contribute not only to GHG reduction, but also to create secure and diversified energy markets and to generate socio-economic development in rural areas (Eriksson 2002). However, the use of biomass at a large scale may create problems related to the logistics of production and sustainable management. Furthermore, different countries use diverse types of biofuels. Although neighbours, Sweden and Norway have developed different energy strategies and utilize bioenergy in different ways (Bjørnstad 2005).

Norway is an energy rich country. In the past fifty years, the use of fossil fuels and hydro-electric power has predominated compared to the use of wood for heating. Bioenergy, including fuel wood, has contributed only 5% of domestic energy consumption, while electricity has provided the largest share of energy consumption (i.e., 50%). Only 1% of the total energy production is generated in district heating (Statistics Norway 2011). Bioenergy production in Norway has been limited due to little investment and few incentives (IEA 2009). On the contrary, bioenergy production in Sweden has had a high share of about 29% (Swedish Energy Agency 2008). Sweden has doubled its proportion of bioenergy production over 30 years ago, thanks in part to heavy subsidies and tax incentives. In only one year Sweden has registered an increase of 12 TWh in bioenergy, while Norway could take the next 10 years to attain that increase (Svebio 2011). Therefore, in Sweden biofuels have been burned commonly at plants designed to produce both heat and electrical power, with links to district heating systems. The main source of wood fuel has been chips from forest residues and by-products from sawmills. However, the

demand for wood fuels has increased the requirement for raw materials from different sources and the variety of types of wood by-products. A possible additional source to help satisfy Swedish demand could be to import raw materials from neighbouring Norway, where there could be a potential surplus of woody biomass.
In this study, we assess GHG emissions and energy use of three WFSCs based on forestry. These three case studies differ in three main features: i) the sources of the wood fuel (i.e., lowland and mountain forests), ii) transit distance, to a district heating plant (DHP) within Norway, and to combined heat and power (CHP) plant in Sweden, and iii) efficiency of bioenergy production (i.e. low in Norway and high in Sweden). The main objectives of the study are to provide empirical data on the relative and absolute effects of the three above mentioned factors.
The paper is structured as follows:

- overview of previous studies connected to WFSCs;
- description of case studies;
- estimation of GHG emissions and energy use of each case study;
- GHG balance of replacing fossil fuels and electricity by forest fuels at the bioenergy plants;
- cost analyses;
- main conclusions.

1.1 Overview of studies

In the past 20 years, several WFSCs have been studied in Scandinavia. Eriksson and Björheden (1989) analysed how to optimize a productive supply chain in Sweden. Forsberg (2000) performed a life cycle inventory of a specific bioenergy transport chain, calculating air pollution and energy use in each step of the supply chain. Hansson et al. (2003) examined different supply systems in relation to energy use and air pollution for providing biofuels to a CHP in Sweden. Studies related to the way of transport have been performed by Lindholm and Berg (2005). Environmental load and energy use of long transport distance systems were assessed in relation to the use of different fuels, including biofuels. González-García et al. (2009) simulated different scenarios for delivering wood to a Swedish pulp mill. Eriksson and Gustavsson (2010) studied Swedish wood chip supply chain and compared Swedish and Finnish bundle systems. Kärhä (2010) studied the industrial supply chain based on wood chips in Finland. Hakkila (2004) evaluated several alternative for forest fuel production system based on wood chips in Finland.
Examples of studies from other European countries come from Van Belle (2003) that analyzed a forest fuel supply chain for providing forest residues to power plant in Belgium and Damen and Faaij (2006) that performed a greenhouse gas balance of international biomass import chain to Netherlands. A regional fuel wood supply chain, including the use of terminal, was assessed by Kanzian (2009) in Austria. Models related to the supply chain of biofuels were made by Gronalt and Rauch (2007) and Emer et al. (2010) respectively in Austria and in Italy. Cherubini et al. (2009) performed an overview of bioenergy chain including forestry residues chain performing energy and GHG balances in comparison to reference system based on fossil fuel.
Our study differs from these previous studies because of: the exportation of wood fuels from Norway to Sweden, the introduction of woody biomass from mountain forests in the WFSC and the assessment of GHG emissions and costs at the same time.

Material & Methods

2.1 Estimation of GHG emissions, energy use and costs

GHG emissions and energy use were determined by performing a life-cycle assessment (LCA), a method to estimate environmental impacts of a product or service throughout its life from

extraction of the raw materials to consumption by the end user (Baumann and Tillman 2004). It is considered one of the best methods for evaluating bioenergy systems in relation to GHG and energy use (Cherubini et al. 2009). LCA considers the interdependencies between all phases of the analyzed system. We used LCA to compare alternative systems based on the case studies. Case studies have been a common method applied in several disciplines of science, although scientific generalization may not be possible if based on a single case. Nevertheless, we argued that comparative case studies is a good way for testing hypotheses and helping to develop scientific innovation, thereby increasing knowlegde (Flyvbjerg 2006).
The key elements of the LCA have been defined in agreement with ISO standard (ISO 2006a, ISO 2006b). The category of environmental impact under assessment was climate change. The global warming potential with a time horizon of 100 years (GWP) was the characterization factor, based on emissions from carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), or GHG (IPCC 2006). In this study, 1 m^3 of solid over bark (s.o.b.) of woody biomass delivered to the bioenergy plant was the selected functional unit, as the base of calculation, allowing comparison between different systems. GWP and energy use were determined as kg $CO_{2equivalent\ (e)}$/m^3 s.o.b. and kWh/m^3 s.o.b., respectively. Results related to forest energy were also presented in MWh in brackets.
At the bioenergy plant, the greenhouse gas balance shows the ratio between the amount of GHG saved using wood fuel at each bioenergy plant and the amount of GHG produced by a reference system based on fossil fuels or electricity to generate heat or combined heat and electricity. A sensitivity analysis was made to test the robustness of the results and identify the most critical unit processes. A cost analysis was also performed using normal economic analyses based on the comparison of prevalent market prices for each country (NOK/m^3 s.o.b.).

2.1.1 System boundary and case studies

The system boundary, illustrated in Fig. 1, includes the entire wood fuel supply chain (WFSC). It is constituted by two parts: the wood fuel production chain (WFPC) and the forest fuel production chain (FFPC).
According to the Swedish Standards Institute (SIS 2004), wood fuels were defined as all types of biofuel originating from woody biomass; that is in our case, biomass from trees and logging residues. In our study, the wood fuels came in the form of wood chips. The forest fuels, defined as wood fuel produced by raw materials without having another use, are wood chips from mountain forests with half derived from logging residues (i.e., tree tops and branches) and half from small trees, while wood chips from lowland forests derived from conventional round wood.
In case study 1, the raw materials, mainly round wood from local lowland forests were chipped at the terminal of Rudshøgda (Oppland county), owned by Mjøsen, a forestry association. The storage capacity at the terminal was 75000 m^3 loose volume (63830 MWh) in two separately covered piles of dry and wet chips. During our study, this terminal did not have a direct connection with the railway, so all wood chips were transported by container trucks to local consumers. In 2010, the DHP of Børstad (Hedmark county), owned by the local Norwegian energy company Eidsiva, was the main consumer of wood chips, taking about 38500 m^3 loose volume (32766 MWh).
In case study 2 and 3, the raw materials were assumed to come from forests located in lowland and mountain areas, respectively. About 35% of the total forested area of Hedmark and Oppland counties is covered by mountain forests, indicating a large potential supply of raw materials for bioenergy purposes (Valente et al. 2011). In case study 2, all raw materials coming from lowland forests were transported to be chipped at the terminal of Sørli, owned by the Norwegian State Railways company (NSB). In 2010, 75% of the wood chips, about 90000 m^3 loose volume (76596 MWh), were exported from this terminal by train to the CHP plant of Skoghall Mill in Sweden (Fig. 2), and 25%, about 40000 m^3 loose volume (34042 MWh), were used locally. Skoghall Mill is a Swedish manufacturer of carton-board for packaging and printing purposes owned by Stora Enso, a worldwide leading paper, packaging and wood products

company. Skoghall Mill buys electricity and fuels from external suppliers while also producing electricity and heating steam itself. 70% of this internal production is based on bioenergy. The energy production based on Norwegian biofuels represented a marginal quantity of the Skoghall Mill production.
In case study 3, 33000 m^3 loose volume (28085 MWh) of wood chips from mountain forests were collected at the terminal at Elverum. The logging residues arrived to the terminal in bundles (Valente et al. 2011) and were assumed to fill up the train from Sørli terminal. Chipping, loading and transport operations of case study 2 were assumed to be as in case study 3.
All wood chips were dried over summer to attain better fuel quality.
Each terminal owned one chipper and a front loader mounted on an excavator for loading chips and making piles.
The transportation routes (Fig. 2) covered distances of: 22 km by truck between Rudshøgda terminal and the Børstad plant at Hamar in case 1, 285 km between Sørli and Skoghall Mill (i.e., 134 km by diesel train, and 151 km by electric train) passing by Elverum in case study 2 and 3. Hector rail is the company provider of train. Diesel trains were used instead of the electrified line in order to avoid the transit in Oslo area.

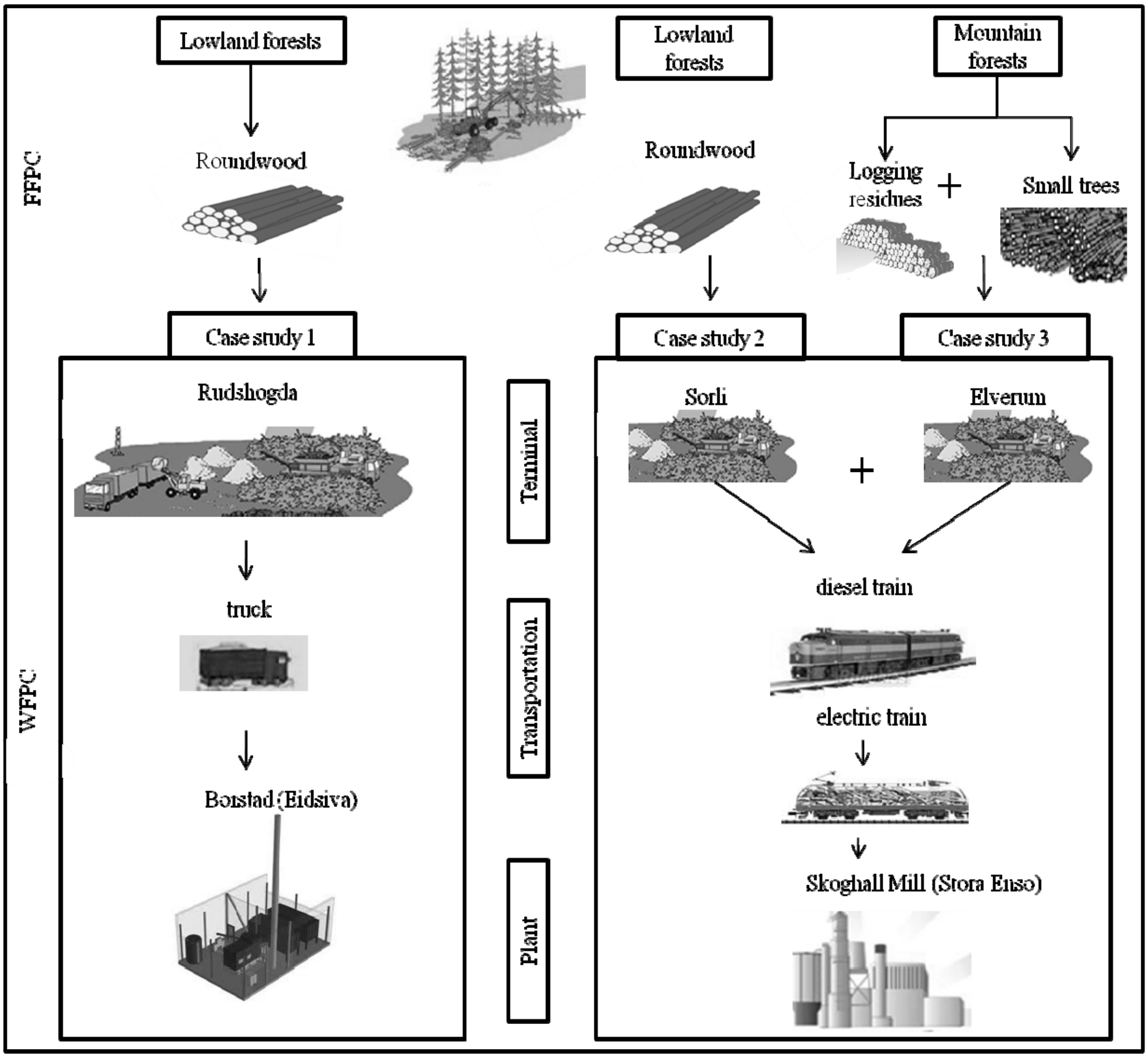


Figure I. *System boundary of the wood fuel supply chain*

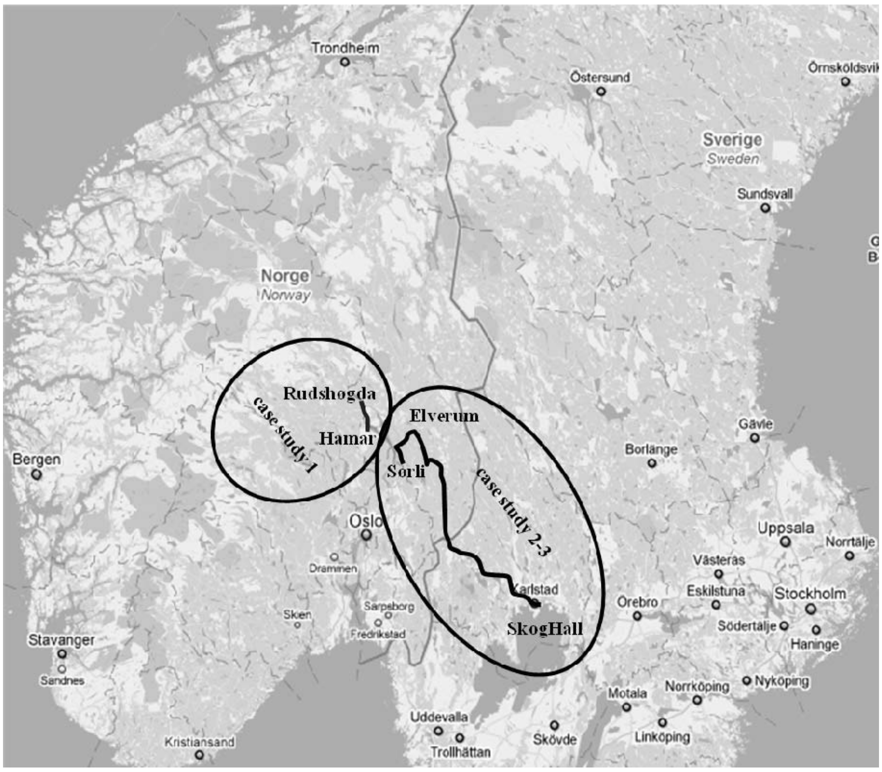


Figure II. *Map of case study 1, 2 and 3*

2.1.1.1 Data collection and assumptions

Reliable data for 2010 were necessary to carry out our work and quantify inputs and outputs of each unit process. Data were obtained from interviews and literature sources (Table 1 and 2) for each case study. The fuel consumption of chipping and loading operation was identical in all case studies due to the use of the same types of machinery. The conversion factor for transforming m^3 loose into m^3 solid over bark was 2.5, while it was 0.47 for transforming m^3 solid over bark into MWh (ÖNORM 1998). Moisture content of wood chip was between 20% and 40% for round wood and around 40-60% for logging residues (personal communication$_a$ 2011). Storage time was less than 1 year. The energy content of diesel was 10.1 kWh. The environmental load of the FFPC (Fig. 1) was estimated using data related to GHG from a Norwegian case study by Michelsen et al. (2008) for lowland forests and Valente et al. (2011) for mountain forests. The FFPC included silviculture, planting, harvesting, forwarding and transportation to the terminal. Bundling of forest residues was integrated in the mountain FFPC. The average transport distance of round wood from lowland forests was 43 km (personal communication$_a$, 2011) and 64 km from mountain areas (Valente et al. 2011). For the homogeneity with Valente et al. (2011), planning, seedling production and forest road construction were excluded from the study by Michelsen et al. (2008) and the results were converted in m^3 solid over bark. The estimates of environmental loads for the FFPC were then added to those for the WFPC (Fig. 2).

An energy input-output ratio was performed for expressing the energy efficiency of a fuel system based on woody biomass. It was reported in percentage as a product among fuel consumption and the energy content of diesel fuel divided by the energy output or heating value of wood chips at the combustion plant (2000 kWh/m^3 s.o.b.). A sensitivity analysis was performed for the WFPCs, assuming an increase and decrease of 10% and

20% of the fuel consumption for each unit process with the aim of verifying the effects on the energy use.

In the calculation of GHG balance, it was assumed that our wood fuel substituted a heating plant based on natural gas, coal or electricity in Børstad and a power plant based on natural gas, coal, or oil in Skoghall Mill. Estimated emissions from these types of plants were obtained from KTH (2008) and Lindholm (2010), respectively. Emissions from the combustion of wood chips were estimated according to Fahlberg and Johansson (2008) in Børstad and Wihersaari (2005) for Skoghall Mill. Efficiency, installed capacity and emissions of both plants based on wood and non-wood fuel (Table 3) were based on the assumption of carbon neutrality, i.e., CO_2 emissions into the air by combustion of wood fuel was balanced by its capture through forest growth. Consequently, only CH_4 and N_2O were emitted into the atmosphere. Emissions from electricity were based on the Nordic electricity mix, i.e., bilateral electricity trade between several market actors arranged by the Nordic Pool exchange. Data related to cost analyses were obtained from interviews (personal communication$_a$, 2011) and energy reports from Norway (Tekniske Nyheter DA 2011) and Sweden (SCB 2010). Internal reports were consulted in Børstad (KMP 2010, Larsson 2010) and in Skoghall Mill CHP plant (STORAENSOa 2010, STORAENSOb 2010, STORAENSOc 2010, STORAENSOd 2011) for making an inventory of non-GHG emissions from both bio-boilers. Regarding the cost analysis, the prices were assumed to be 10% higher than the cost of the wood chips delivered at the plants.

Table 1. Data collection case study 1

Raw materials (wood chips)	Volume		
Terminal: Rudshøgda	75000 m^3 loose/year (63830 MWh)		
Delivered to Børstad	38500 loose m^3/year (32766 MWh)		
Unit process	Fuel consumption		
chipping	1.2 l/m^3 s.o.b. (2,5 l/MWh)[a]		
loading	0.2 l/m^3 s.o.b. (0,4 l/MWh)[a]		
chip truck	2.16 l/m^3 s.o.b. (6,2 l/MWh)[b]		
Transportation	Rudshøgda-Børstad: 22 km		
	number	loading capacity	number containers
container truck	3	90-100 m^3 loose (76-85 MWh)	2-3 per truck
total trip/year	330 truck/year	-	

[a] Mjøsen Skog BA, Per Magne Bryhn (personal communication$_a$, 2011)
[b] Hohle (2008)

Table 2. Data collection case study 2 and 3

Raw material (wood chips)	Volume		
Terminal: Sørli	130000 m^3 loose/year (110638 MWh)		
Terminal: Elverum	33000 m^3 loose/year (28085 MWh)		
Delivered to Skoghall Mill	123000 m^3 loose/year (104681 MWh)		
Unit process	Fuel consumption		
chipping	1.2 l/m^3 s.o.b.[a] (2.5 l/MWh)		
loading	0.2 l/m^3 s.o.b.[a] (0.4 l/MWh)		
transport diesel train	0.33 l/m^3 s.o.b.[c] (0.7 l/MWh)		
transport electric train	1.96 kWh/m^3 s.o.b.[c]		
Transportation	Sørli-Skoghall Mill: 285 km		
	number	loading capacity	number containers
freight train [d]	32/year	1537 m^3 solid/train (3270 MWh)	70/train

[a]Mjøsen Skog BA, Per Magne Bryhn (personal communication$_a$, 2011)
[C] Hector Rail AB, Lennart von der Burg (personal communication$_b$, 2011)
[d] Stora Enso Skoghalls Bruk, Leif Löfgren (personal communication$_c$, 2011)

Table 3. Efficiency and installed capacity of bio-boiler in Børstad and Skoghall Mill and emissions from wood and not wood combustion plant

Bio-boiler	installed capacity (MW)	efficiency (%)
Børstad	5	85
Skoghall Mill	135	87
Emission from wood chips combustion	kg CO_{2e}/m^3 s.o.b.	kg CO_{2e}/MWh
Børstad	5	10
Skoghall Mill	1	2
Emissions from heating plant		
natural gas	104	221
oil	212	451
electricity	38	81
Emissions from cogeneration plant		
natural gas	179	380
coal	368	783
oil	187	368

Results

The WFPC of case study 1 (Fig. 3) had total GWP equal to 10.84 kgCO_{2e}/m^3 s.o.b. (23.06 kgCO_{2e}/MWh), while the total energy use was 36.46 kWh/m^3 s.o.b. Transportation by truck had the highest GWP (6.5 kgCO_{2e}/m^3 s.o.b. or 13.83 kgCO_{2e}/MWh) and energy use (22 kWh/m^3 s.o.b.).

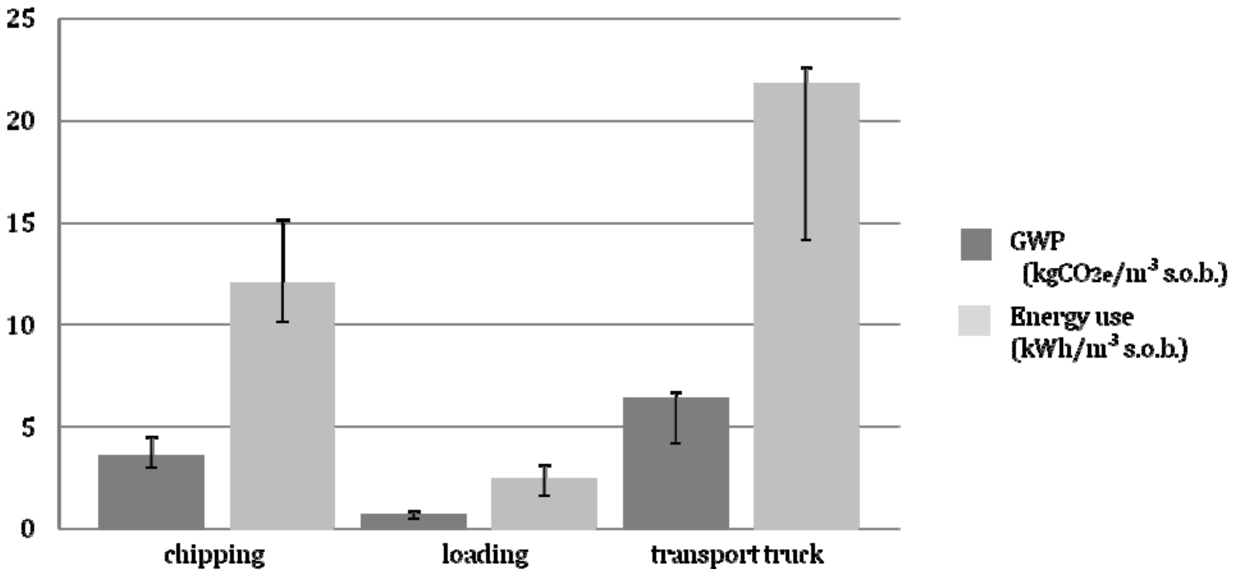


Figure III. Case study 1: GWP and energy use of the wood fuel production chain. Error bars indicate the variation of the results in relation to different values of fuel consumption from studies performed in Nordic countries (Hansson 2003, Hohle 2008, Michelsen et al. 2008, González-García et al. 2009).

Both WFPCs of case studies 2 and 3 had a total GWP of 5.3 $kgCO_{2e}/m^3$ s.o.b. (11.3 $kgCO_{2e}$/MWh) and energy use of 19.9 kWh/m^3 s.o.b. (Fig. 4), about half that of case study 1. The highest share of GWP (3.6 $kgCO_{2e}/m^3$ s.o.b. or 7.7 $kgCO_{2e}$/MWh) and energy use (12 kWh/m^3 s.o.b.) was from the chipping operation, while the lowest was from transportation with electric train.

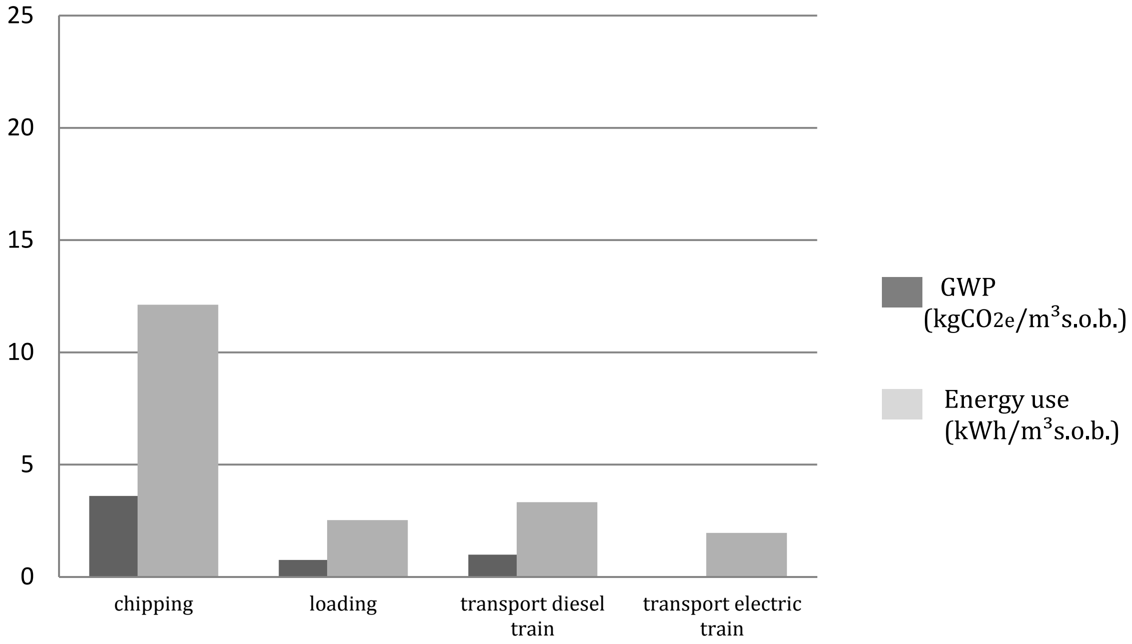


Figure IV. Case study 2 and 3: GWP and energy use of the wood fuel production chain.

The lowland and mountain FFPC (Fig. 1) had total GWP of 15.9 kg CO_{2e}/ m^3 s.o.b. (33.8 kg CO_{2e}/MWh) and 17.6 kg CO_{2e}/ m^3 s.o.b. (37.4 kg CO_{2e}/MWh), respectively.

The GWPs of WFSC were 31.7 kg CO_{2e}/m^3 s.o.b. (67.4 kg CO_{2e}/MWh) for case study 1, 22.2 kg CO_{2e}/m^3 s.o.b. (47.2 kg CO_{2e}/MWh) for case study 2, and 23.9 kg CO_{2e}/ m^3 s.o.b. (50.8 kg CO_{2e}/MWh) for case study 3. When the FFPC was included in the calculation, the GWP of case study 1 was still 9.5 kgCO_{2e}/m^3 s.o.b. (20.2 kg CO_{2e}/MWh) for case study 2 and 7.7 kgCO_{2e}/m^3 s.o.b. (16.4 kg CO_{2e}/MWh) for case study 3 higher than case study 1.

In the WFSC (Fig. 5), the mountain FFPC (case study 3) used 3% more GWP than the lowland FFPC (case study 2). Compared to case study 1, the WFPC in cases study 2 and 3 had 10% and 12% lower shares of GWP, respectively. The combustion part of case study 1 had 11% and 12% greater GWP than case studies 2 and 3, respectively.

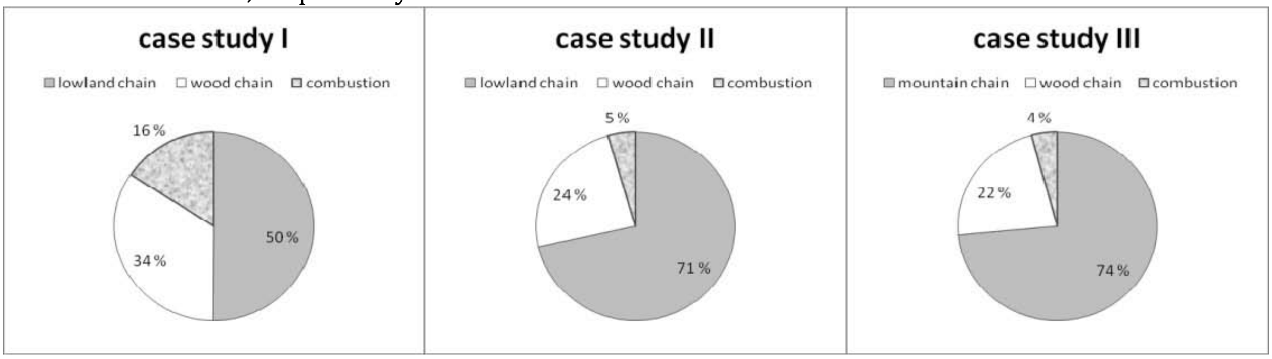


Figure V. Overall GWP in percentage for case study 1, 2 and 3.

The energy input-output ratio showed that for case study 1, 2 and 3 respectively it was necessary a fossil fuel energy input of 4.8%, 3.6% and 4.3% for producing energy output based on wood fuels.

Fig. 6, 7 and 8 illustrate the GHG balance of each case study. The GHG balance for case study 3 suggested that it consumed 1.7 kg CO_{2e} /m^3 s.o.b. (3.6 kg CO_{2e}/MWh) more than that for case study 2. Indeed, in case study 1 the reference system based on electricity had the lowest emissions per functional unit (38 kg CO_{2e}/m^3 s.o.b. or 81 kg CO_{2e}/MWh). In case study 2, the replacement of natural gas plant, for example, allowed saving 80 kgCO_{2e}/m^3 s.o.b. (170 kg CO_{2e}/MWh) more than in case study 1.

In all the case studies, the substitution of coal with wood fuel had the highest reduction in the GHG emissions.

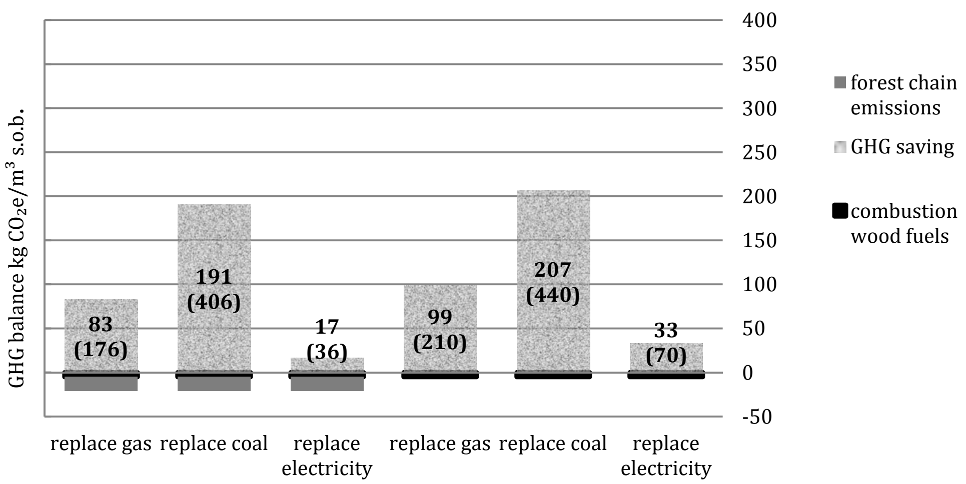


Figure VI. GHG balance of case study 1. The negative part of the chart represents the emissions not compensated by the substitution of fossil fuel and electricity with wood fuel.

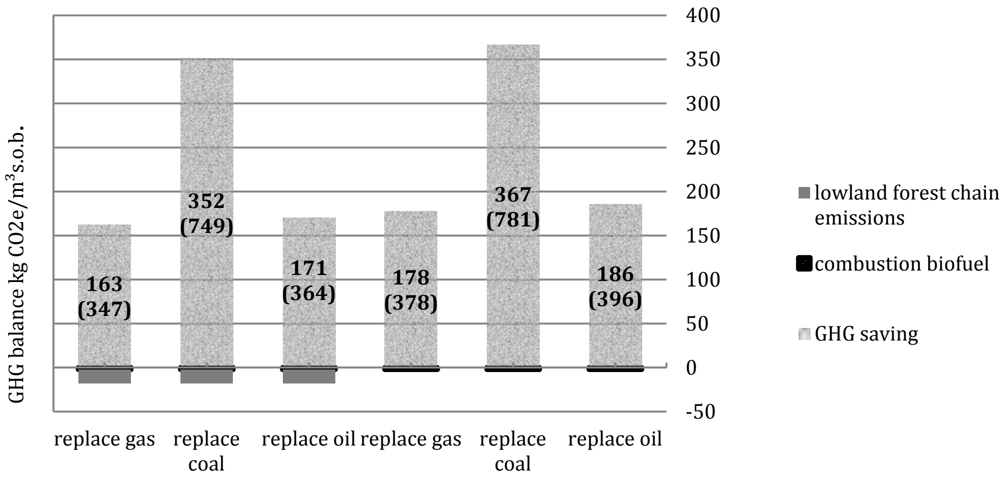


Figure VII. GHG balance of case study 2. The negative part of the chart represents the emissions not compensated by the substitution of fossil fuel with wood fuel.

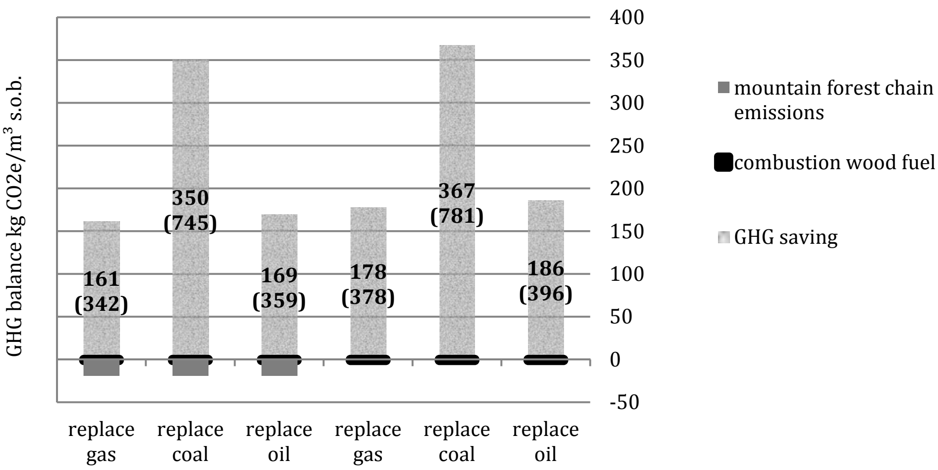


Figure VIII. GHG balance of case study 3. The negative part of the chart represents the emissions not compensated by the substitution of fossil fuel with wood fuel.

The sensitivity analysis of the WFPC (Fig. 9) showed that the change in the input parameter fuel consumption influenced significantly the energy use of transport based on diesel truck and chipping operation.

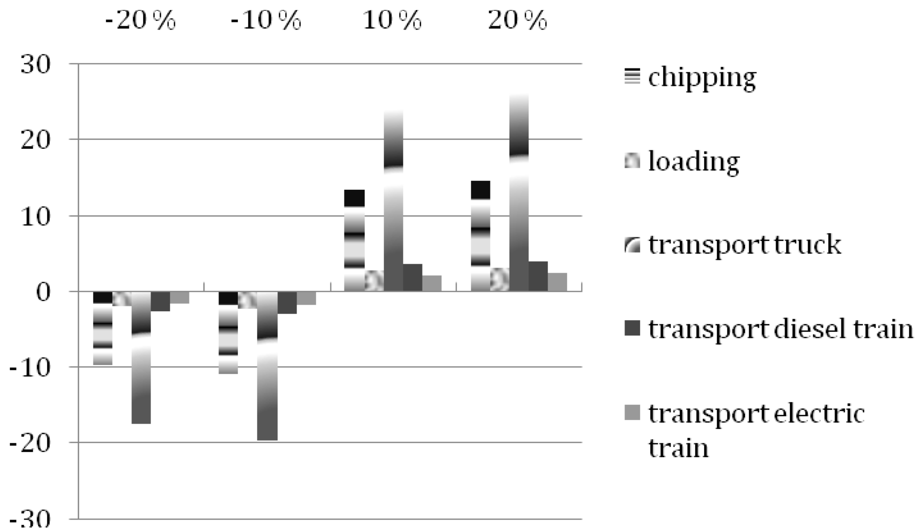


Figure IX. Sensitivity analysis of the WFPCs: decrease and increase of 10% and 20% of the parameter fuel consumption and affect on the energy use (kWh/m³ s.o.b.).

3.1. Non-GHG emissions

The bio-boiler in Skoghall Mill (case study 2 and 3) had lower estimated NO_X emissions, but higher CO emissions (more than double) and dust (2 mg/m³ more) than the bio-boiler in Børstad (case study 1) (Table 3).

Table III. Inventory of Børstad and Skoghall Mill bio-boilers. Emissions of NO_X, NH_3, CO, SOX, dust, total organic component (TOC) and ash content have been measured at normal pressure and temperature by accredited test laboratories.

Parameters		Børstad	Skoghall Mill
NO_x	kg NO_x/MWh	0.21	0.18
CO	mg/Nm3 (6 % 0_2)	42	100
SO_x	kg SO_x/MWh	n.a.[e]	0.05
dust	mg/Nm3	< 5	7.3
TOC (mainly CH_4 and CH_3)	mg/Nm3	n.a.	< 2-3
NH_3	mg/MJ	n.a.	6.34
ash content	dry matter	1.6%	n.a.

[e] n.a. not available

3.1.1. Cost analyses

Results of cost analyses were illustrated in table 4. Low moisture content (< 35%) corresponded to higher costs of wood chips. At the Børstad plant (case study 1) the cost increase was 16 NOK/m³ s.o.b. (34 NOK/MWh). The difference in cost between the wood chips bought at Skoghall plant (case study 2 and 3) and the average cost at Børstad was 34 NOK/m³ s.o.b. (72 NOK/MWh).

Table IV. Cost comparison with the average market prices

costs	
cost of raw materials at the terminal	6 NOK/m^3 s.o.b. (13 NOK/MWh) (personal communication$_a$, 2011)
cost of chipping operation	50 NOK/m^3 s.o.b. (106 NOK/MWh) (personal communication$_a$, 2011)
cost of wood chips at Børstad	105 NOK/m^3 s.o.b. (223 NOK/MWh), moisture content <35% 89 NOK/m^3 s.o.b. (189 NOK/MWh), moisture content > 35% 97 NOK/m^3 s.o.b. (206 NOK/MWh) in average
cost of wood chips at Skoghall Mill	72 SEK/m^3 s.o.b.[f] (153 NOK/MWh) equivalent to 63 NOK/ m^3 s.o.b. (134 NOK/MWh)

[f] 1 SEK= 0.87 NOK

Discussion

This study supported our idea that wood fuel can be exported from Norway to Sweden without losing environmental and economic benefits. Case 1, i.e. the local WFSC, had the highest GWP and energy use within all three case studies, mainly due to road transportation system and higher emissions at the combustion plant. The WFSC of case 2 and 3 differed little in the GWP and energy use (Fig. 4), even though the mountain FFPC (case 3) produced greater emissions and had higher energy use than the lowland FFPC (case 2). The energy input-output ratio indicated that case 1 requires 1.2% more energy input than case 2. Little difference in energy use between case 1 and 3 supported our hypothesis that the introduction of mountain FFPC into the WFSC may not greatly increase both GHG emissions and energy demand. Low level of energy input (i.e., less than 5%) was required in all our case studies to produce bioenergy, confirming the results of Wihersaari (2005) and Kariniemi (2009).
The benefits of producing bioenergy from woody biomass were evident in all case studies at the conversion plant, because of the replacement of fossil fuel and electricity.
The GHG balance, including even emissions due to the use of fossil fuel along the WFPCs and at the conversion plants, was positive especially when the considered wood chip plants replaced coal and oil plants. Large amount of GHG emissions can be eliminated by the replacement of fossil fuel with biofuel (Wihersaari 2005).
The GHG balance was better at the Skoghall Mill (case 2 and 3) when compared with the Børstad plant (case 1). At the CHP plant of Skoghall Mill, the cogeneration of heat and power and the use of wood fuel made it more efficient, compared to smaller system as Børstad DHP which needed higher quality fuels. This suggested that large-scale efficient combustion systems may utilize low quality fuels. At the Skoghall Mill CHP plant, introduction of a boiler using wood chips and renovation of boiler using black liquor resulted in reducing oil consumption by 90000 m^3 from 2005 to 2010. Nevertheless, it is important to remember the differences between the Norwegian and Swedish plants. The Skoghall Mill is one of the most modern paperboard mills in the world, where cogenerated energy was both consumed and produced. The use of wood fuels makes it possible both to sell permissions for emitting CO_2. In the period of less demand for paper products, a good alternative is to sell electricity based on wood fuels instead of producing paperboard. Moreover, the surplus of energy can be delivered to the district heating network, constituting a further income for this mill. On the other hand, Børstad is a smaller plant that lacked cogeneration capabilities, poorer treatment of flue gases and a bio-boiler 26 times smaller than the Skoghall Mill plant.

In all WFPCs, chipping operation had the highest GWP and energy use and it was one of the most sensitive processes to changes in fuel consumption. The substitution of diesel powered chipper with electric chipper might be a solution for reducing the GHG emissions.
The demand for wood biomass at power plants in Sweden was estimated to increase by 50 PJ between 2007 and 2015 (SFA 2008). As a result, in future Skoghall Mill could need to import increasing quantities of wood fuels from Norway.
This increasing demand could lead to intensify the harvesting of tree stumps for bioenergy purposes, with ecological consequences in terms of biodiversity loss and reduced carbon storage (Egnell et al. 2007, Hjältén et al. 2010, Melin et al. 2010). An option can be to use small trees and logging residues from Norwegian mountain forests, in the respects of both the environment and the forest laws. However, specific studies on the removal of this woody biomass on biodiversity, forest soils and carbon storage are unknown and should be studied.
The present study suggests that the combination of harvesting forest residues, chipping at the terminal, transportation distance based on railroad and large scale plant has a great potential of expansion, confirmed by previous study (Forsberg 2000, Tahvanainen and Anttila 2010, Wihersaari 2005). A steady demand throughout the year, the need of storage wood fuel especially from mountain areas and a save supply make strategic the use of the terminal (Kanzian 2009). In addition, chipping at the terminal is a good alternative for avoiding noise and dust at the bioenergy plant, often close to urban areas. However, the studied terminals reported large amount of rotten wood, that cannot be handled in the conversion plant of Børstad, as mentioned above, but they are exported to the Swedish CHP plant. Thus, this fact confirms that low quality wood as from mountain forests can be exported from Norway to Sweden. Forest fuels from mountain areas have potential for filling up the Swedish demand and more sophisticated and efficient technologies might decrease the emissions and the costs of extraction. This means that the transport distance will become longer and alternative transport as electric trains become preferable. The increment of train transportation will have lower GHG impacts than transportation by trucks, confirming the results from previous studies (González-García et al. 2009; Lindholm and Berg 2005). The use of train requires less amount of energy, and it is a more efficient and clean system.
Study from Tahvanainen and Anttila (2010) related to supply costs identifies supply based on train as the most cost effective even when the transport distance is shorter than 100 km. These elements support the idea of introducing railroad in the terminal of Rudshøgda (case 1). However, at the moment the Norwegian railway network is under developed and quite costly.
In Norway, electric trains use mainly hydroelectric energy, producing almost zero emissions. Nevertheless, according to the rules of the Nordic electricity mix, in dry or cold year Norway is a net importer of electricity based on not renewable energy source, producers of GHG.
The GHG emissions from transportation can be further reduced by using in a better way the loading capacity of transports systems, choosing the roads optimally and improving transport technologies.
Example is provided by the difference in payload between Swedish and Norwegian trucks. The total weight of a truck with a trailer is 60 tonnes in Sweden and 54 tonnes in Norway. Lower loading capacity can increase the fuel consumption of the Norwegian trucks. A suggested solution it is to increase the loading capacity of Norwegian trucks or replace trucks powered by fossil fuels with ones powered by biofuels. A further option is to use diesel trains having lower energy consumption and CO_2 emissions than diesel trucks (NSB 2011).
Regarding the costs, Skoghall Mill can be expected to buy Norwegian chips at lower price than the national average prices. The prices of wood chips at Børstad plant are much higher than the average in Sweden. This means that in Norway the cost of wood chips is more expensive. In addition, the cost of wood chips, as shown in table IV, is related to the moisture content. Skoghall Mill can buy at low price and treat low quality wood chips with high moisture content, as those from Norwegian mountain forest.

It is important to highlight that Sweden can continue to import raw material from Norway until the market prices are economical convenient. In the opposite case, Skoghall Mill can think to import raw material from other countries, starting to use the connection to the sea through the lake Vænern.

Conclusions

Our study highlights how differences in handling wood fuel, transport system and conversion plants modify the amount of GHG emissions and energy use. In the present article, the WFSC with lower GWP and energy use deal with the exportation of wood fuel from Norway to the neighbour country Sweden. Changes in fuel consumption affect critically the energy use of chipping operation and transportation by truck. Railway, even base on diesel train, has less air pollution than road transportation. The energy input-output ratio indicates that all case studies need low amount of energy for producing bioenergy. The harvest of forest fuel having mountain origins, in respect of the environment, can be an additional source of wood fuels to export in a country where the request is elevated as Sweden. In this case, the GHG impact from longer transport distance is compensated by the use of less polluted transport system as electric train and better efficiency at the conversion plant. Substitution of fossil fuel, especially coal and oil, by wood fuel has positive benefits in the mitigation of climate change. Cost analyses show that the current economical advantages of exporting wood chips from Norway to Sweden, although strictly connected to the present market prices. The GHG balance indicates that large CHP plants save more emissions per functional unit compared to smaller plant, due to the high efficiency in the conversion process. In conclusion, our study shows that it is feasible to export wood chips from Norway to Sweden, without increasing dramatically GHG emissions and costs.

Acknowledgements

The authors gratefully acknowledge the support of Eidsiva energy company, Stora Enso Skoghall Mill, Mjøsen forest association and Hector Rail for helping during data collection. We also thank Mike Ferguson for English revision.

Sources cited

Baumann, H. & Tillman, A-M. 2004. The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Lund, Sweden. p. 532

Bjørnstad, E. 2005. An engineering economics approach to the estimation of forest fuel supply in North-Trøndelag county, Norway. Journal of Forest Economics 10(4): 161-188.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B. & Woess-Gallasch, S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling 53(8): 434-447.

Damen, K. & Faaij, A. 2006. A Greenhouse Gas Balance of two Existing International Biomass Import Chains." Mitigation and Adaptation Strategies for Global Change 11(5): 1023-1050.

Egnell, G., Hyvönen, R., Högbom, L., Johansson, T., Lundmark, T. Olsson, B., Ring, E. & von Sydow, F. 2007. Environmental aspects on stump-harvest – compilation of knowledge and knowledge gaps. Energimyndigheten Rapport 40 2007. In Swedish with English summary.

Emer, B., S. Grigolato, Lubello, D. & Cavalli, R., 2010. Comparison of biomass feedstock supply and demand in Northeast Italy. Biomass and Bioenergy. In Press, Corrected Proof.

Eriksson, L. O. & Björheden R. 1989. Optimal storing, transport and processing for a forest-fuel supplier. European Journal of Operational Research 43(1): 26-33.

Eriksson, H., Hall, J. & Helynen, S. 2002. Rationale for forest energy production. In: Richardson, R. B. J., Hakkila, P., Lowe, A.T., Smith, C.T. (eds.). Bioenergy from sustainable forestry. Guiding principles and practice. The Netherlands: Kluwer Academic Publishers. p.1-17.

Eriksson, L. & Gustavsson L. 2010. Comparative analysis of wood chips and bundles - Costs, carbon dioxide emissions, dry-matter losses and allergic reactions. Biomass and Bioenergy 34(1): 82-90.
European Parliament 2009. PE-CONS 3736/08. Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.
Flyvbjerg, B., 2006. Five Misunderstandings About Case-Study Research. Qualitative Inquiry 12 (2): 219-245.
Forsberg, G. 2000. Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method. Biomass and Bioenergy 19(1): 17-30.
González-García, S., S. Berg, Feijoo, G. & Moreira, M. 2009. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. The International Journal of Life Cycle Assessment 14(4): 340-353.
Gronalt, M. & Rauch P. 2007. Designing a regional forest fuel supply network. Biomass and Bioenergy 31(6): 393-402.
Hakkila, P. 2004. Production technology of forest chips. Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999–2003. Report 6/2004. Tekes, National Technology Agency. Helsinki. p.29-49.
Hansson, P.-A., Dahlin, B. & Blinge, M. 2003. Air emissions from the fuel supply system of a Swedish CHP plant and the effects of stricter emission regulations. Biomass and Bioenergy 24(1): 59-68.
Hjältén, J., Stenbacka, F. & Andersson, J. 2010. Saproxylic beetle assemblages on low stumps, high stumps and logs: Implications for environmental effects of stump harvesting. Forest Ecology and Management 260(7): 1149-1155.
Hohle, A. M. E. 2008. Energiforbruk ved høsting av skogbrensel [Energy requirements for harvesting forest fuel]. Master thesis. Norwegian University of Life Sciences. Norway. (In Norwegian).
IEA 2009. Bioenergy task 40 –Sustainable International Bio-energy trade- Country report 2009 for Norway. Norway.
IPCC 2006. Guidelines for National Greenhouse Gas Inventories.Agriculture, Forestry and Other Land Use. Japan, Intergovernmental Panel of Climate Change.
ISO 2006a. International Organization for Standardization ISO 14040, 2006. Environmental management – Life Cycle Assessment – principles and framework. .
ISO 2006b. International Organization for Standardization. ISO 14044: 2006. Environmental management – Life Cycle Assessment – requirements and guidelines.
Kanzian, C., Holzleitner, F., Stampfer, K. & Ashton, S. 2009. Regional Energy Wood Logistics – Optimizing Local Fuel Supply. Silva Fennica 43(1): 113-128.
Kariniemi, A., Kärhä, K., Niininen, M. & Heikka, T. 2009. Feedstock Supply Chain CO2-eq Emissions. A Case Study on Forest Biomass to Liquid Traffic Fuel. Metsätehon katsaus 38.
KMP 2010. Rapport från stoft, CO och NOx-mätningar efter textilfilter på en 5 MW biokjel vid Börstad Varmesentral i Hamar den 16 feb 2010. [Report from dust, CO and NOx measurements for fabric filter at a 5 MW bio boiler of Børstad district heating in Hamar February 16, 2010]. Kontroll Miljö Process AB. Internal report. Eidsiva Bioenergi AS, Hamar, Norway.
KTH 2008. Statistikdatablad emissionsfaktorer 2008-11-25. [Statistics data sheet emission factors]. Industriell ekologi (In Swedish).
Kärhä, K. 2010. Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy. In Press, Corrected Proof.
Larsson, P. 2010. Rapport från stoft, CO och NOx-mätningar efter textilfilter på en 5 MW biokjel vid Börstad Varmesentral i Hamar den 16 feb 2010. [Report from dust, CO and NOx measurements for industrial filter at 5 MW bio-boiler in Börstad in district heating of Hamar February 16, 2010]. Kontroll Miljö Process AB, Västervik, Sweden. (In Swedish).
Lindholm, E.-L. 2010. Energy use and environmental impact of roundwood and forest fuel production in Sweden. Thesis dissertation. Swedish University of Agricultural Sciences. Uppsala, Sweden.
Lindholm E.-L. & Berg S. 2005. Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research 20: 184-191.

Melin, Y., H. Petersson & Egnell, G. 2010. Assessing carbon balance trade-offs between bioenergy and carbon sequestration of stumps at varying time scales and harvest intensities. Forest Ecology and Management 260(4): 536-542.
Michelsen, O., C. Solli & Strømman, A.H, 2008. Environmental Impact and Added Value in Forestry Operations in Norway. Journal of Industrial Ecology 12(1): 69-81..
SFA 2008. Miljöanalys–Stubbskörd [Environmental analysis—Stump harvest], Swedish Forest Agency. (In Swedish).
SIS 2004. Teknisk specififikation SIS-CEN/TS 14588:2003. Solid biofuels- terminology, definitions and descriptions. Swedish Standard Institute. Stockholm, Sweden.
SCB 2010. Trädbränsle- och torvpriser Nr. 3 /2010. 2010-08-31. STATISTISKA MEDDELANDEN EN 0307 SM 1003. Sveriges Officiella Statistik.
Stampfer, K. & Kanzian, C. 2006. Current state and development possibilities of wood chip supply chains in Austria. Croatian Journal of Forest Engineering 27(2): 135-145.
STORAENSOa 2011. CO rapport [CO report]. Internal report. (in Swedish).
STORAENSOb 2010. ÅRSRAPPORT SOx och NOx MKV Panna 11 [Yearly report SOx and NOx MKV boiler 11]. Internal report (In Swedish).
STORAENSOc 2010. NH3, mg/MJ. Internal report (In Swedish).
STORAENSOd 2011. Paper, packaging & forest products. Quality assurance of exhaust gas analysis. Regulations and measurement requirements. Internal report .
Svebio 2011. Rekordökning för bioenergi - motsvarar kärnkraften från Oskarshamn [A record increase for bio-energy-equivalent to nuclear power from Oskarshamn]. Swedish Bioenergy Association. Stockholm, Sweden.
Swedish Energy Agency 2008. Energy indicators 2008 Theme: Renewable energy. ET 2008:21.
Tahvanainen, T. & Anttila, P. 2010. Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass and Bioenergy. In Press, Corrected Proof.
Tekniske Nyheter DA 2011. Energi Rapporten. Årgang 8 Nummer 12 – 2011. [Energy report. Published number 8 12-2011]. Norway (In Norwegian).
Valente, C., Hillring, B.G. & Solberg B. 2011. Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. Scandinavian Journal of Forest Research. In Press. Available on line.
Van Belle, J.-F., Temmerman, M., Schenkel, Y. 2003. Three level procurement of forest residues for power plant. Biomass and Bioenergy 24(4-5): 401-409.
Wihersaari, M. 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28: 435–443.
ÖNORM, M. 1998. Energiewirtschaftliche Nutzung von Holz und Rinde als Brennstoff Begriffsbestimmungen und Merkmale.[Energy-efficient use of wood and bark as fuel definitions and characteristics. Austrian Standards Institute, Vienna]. Österreichisches Normungsinstitut, Wien. (In German).

World Wide Web Sources

NSB 2011. Railway operations and energy consumption. Report, Norway. http://www.nsb.no/nsb-konsernet-og-miljoe/miljoeregnskap-article37643-4492.html. Visited on 30 May, 2011
Statistics Norway 2011. http://www.ssb.no/energi_en/. Visited on 30 May, 2011.

Paper 3

Journal of Cleaner Production 19 (2011) 1931–1938

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy)

Clara Valente [a,b,*], Raffaele Spinelli [c,1], Bengt Gunnar Hillring [a,2]

[a] Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, Anne Evenstadsvei 80, 2480 Koppang, Norway
[b] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, Pb. 5003, NO-1432 Ås, Norway
[c] CNR IVALSA, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Italy

A R T I C L E I N F O

Article history:
Received 14 February 2011
Received in revised form
27 June 2011
Accepted 28 June 2011
Available online 13 July 2011

Keywords:
Alpine forest fuel system
Costs
Direct employment potential
Global warming potential
LCA
Sustainability

A B S T R A C T

An extended Life Cycle Assessment (LCA) is performed for evaluating the impacts of a woody biomass supply chain for heating plants in the alpine region. Three main aspects of sustainability are assessed: greenhouse gas emissions, represented by global warming potential (GWP) impact category, costs and direct employment potential. We investigate a whole tree system (innovative logging system) where the harvest of logging residues is integrated into the harvest of conventional wood products. The case study is performed in Valle di Fiemme in Trentino region (North Italy) and includes theoretical and practical elements. The system boundary is the alpine forest fuel system, from logging operations at the forest stand to combustion of woody biofuels at the heating plant. The functional unit is 1 m^3 solid over bark of woody biomass, delivered to the district heating plant in Cavalese (Trento). The relative sustainability of traditional and innovative systems is compared and energy use is estimated. Results show that the overall GWP and costs are about 13 kg $CO_{2equivalent}$ and 42 euro per functional unit respectively for the innovative system. Along the product supply chain, chipping contributes the greatest share of GWP and energy use, while extraction by yarder has the highest financial costs. The GWP is reduced by 2.3 ton $CO_{2equivalent}$ when bioenergy substitutes fuel oil and 1.7 ton $CO_{2equivalent}$ when it substitutes natural gas. The sensitivity analysis illustrates that variations in fuel consumption and hourly rates of costs have a great influence on chipping operation and extraction by cable yarder concerning GWP and financial analysis, respectively. This is confirmed by sensitivity analysis. Better technologies, the use of biofuels along the product supply chain and more efficient systems might reduce these impacts. Replacing the traditional system with the innovative one reduces emissions and costs. A low energy input ratio is required for harvesting logging residues. The direct employment potential is a conflicting aspect and needs further investigations.

1. Introduction

International and national policies support the utilization of renewable energy and bioenergy for several purposes i.e. climate change mitigation, energy supply security and energy source diversification. The Kyoto protocol agreement (United Nations, 1998), the European Union target of a 20% reduction in greenhouse gas emissions (GHG) emissions, energy consumption and energy based on fossil fuels (European Union, 2009), and the assumption of carbon neutrality for biomass (International Energy Agency, 2007) are the main drivers behind the implementation of bioenergy production. Along the Alps, local communities show high levels of awareness regarding renewable energy sources, while provincial policy-makers have a keen concern for environmental protection, and are open to the use of bioenergy for mitigating the effects of global warming.

In this perspective, mountain forests can play an important role as source of raw material for energy purpose. In the Alps, the use of woody biomass for energy can stimulate an active forest management. The preservation of wood production for commercial purposes is very valuable for the management of the alpine areas (Giovannini, 2004). It is important to maintain an economic interest in timber production, in order to limit abandonment and the consequent decay of forest stands, as has happened in alpine

* Corresponding author. Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, Anne Evenstadsvei 80, N-2480 Koppang, Norway. Tel.: +47 62430846.
E-mail addresses: clara.valente@hihm.no (C. Valente), spinelli@ivalsa.cnr.it (R. Spinelli), bengt.hillring@hihm.no (B. G. Hillring).
[1] Tel.: +39 055 5225641.
[2] Tel.: +47 62430859.

0959-6526/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2011.06.026

regions. However, the use of woody biomass for energy should occur on a sustainable basis, i.e. its utilization should not cause negative impacts, or damage the availability of natural resources in the long run.

The aim of this paper is to present an example of an alpine forest fuel system performing a life cycle assessment, based on integrating the harvest of logging residues with the harvesting of conventional wood products (saw logs). The main objectives of the study are to:

- assess the GHG emissions, the financial cost and the direct employment potential;
- compare two logging systems – traditional (short wood system or SWS) and innovative (whole tree system or WTS) – in terms of GHG emissions, costs and effects on employment;
- evaluate the energy use of each unit process involved in the studied chain;
- highlight the most sensitive elements.

1.1. Overview of forestry studies in a life cycle assessment prospective

Several studies concerning the evaluation of the impacts of forest operations through the life cycle assessment methodology are performed in Nordic countries. Examples come from Berg (1997), Berg and Lindholm (2005) and Athanassiadis (2000) in Sweden. Forest technologies systems, in the first study, and forest operations in different parts of Sweden in the second one, are compared for finding out the system with less emissions and energy use. Athanassiadis calculates fuel consumption and GHG emissions for logging operations. Primary energy and long transportation distance are studied in Finland (Karjalainen and Asikainen, 1996). Berg and Karjalainen (2003) compare the GHG emissions of forest operations between Sweden and Finland. In an European context Schwaiger and Zimmer (2001) compare fuel consumption and GHG emissions. González-García et al. (2009) compare two case studies from Sweden and Spain regarding the environmental impacts of forest production and supply of pulpwood. In USA Sonne (2006) studies GHG emissions of forestry operations in the Pacific Northwest coast. However, all these studies are performed in lowland conditions, excluding both the integration of bioenergy in the forest operations and socio-economic aspects.

1.2. Background

A case study was performed in Valle di Fiemme, in the province of Trento (Italy) (Fig. 1) in the year 2010. In Italy, this province (region Trentino-Alto Adige) is at the forefront both in the forestry sector and in conservation of the environment. Around 17% of the land of the Trento province is covered by national parks and regional reserves. This province has invested heavily in the *Natura 2000* European network, where sites with a specific value to nature are placed under a special protection regime for the conservation of biodiversity. Hence, around 28% of the territory in the Trento province is managed both for nature conservation and habitat improvement.

The economy of Trentino is mainly based on tourism. The development of tourist activities goes hand in hand with the increased role of forests for recreation (Wolynski et al., 2008). Hence, there is growing economic interest in the conservation of the landscape and in the enhancement of its hedonic value (Provincia autonoma di Trento, 2009). Forest management follows the rule of *nature based silviculture*, where the biological stability and the fertility of the forest stand are safeguarded (Piussi, 1994). Consequently there has been a steady effort to limit clear cutting, to introduce continuous cover forestry and to foster natural regeneration. Local silviculture generally aims to restore the composition of the vegetation, by tuning the balance between structure and volume, in relation to the geographic location (Diaci, 2006).

2. Goal and scope of the LCA

The methodological approach is Life Cycle Assessment (LCA) as recommended by International Standards Organization (ISO, 2006a,b). Several methods (Environmental Impact Assessment, Energy Analysis, Strategic Environmental Assessment etc.) exist for evaluating environmental impacts as suggested by Finnveden and Moberg (2005). However, LCA is the tool more adapted to the

Fig. 1. Map of Valle di Fiemme, located in Trentino-Alto Adige region (North Italy), indicated by arrows.

current study, as analytical method for targeting the significant points in the life cycle of the woody biomass product. The key elements pointed out by the LCA definition of Glavic and Lukman (2007) are followed: identification and quantification of the environmental loads, assessment of the potentiality of these loads and proposal of environmental impacts reduction.

GHG emissions, i.e. CO_2, CH_4 and N_2O, are calculated for each step of the production supply chain, including combustion at the heating plant. Our focus is limited to standing woody biomass of the trees while carbon stored in the soil is not taken into account. Furthermore, a socio-economic assessment is performed, through the evaluation of financial costs and direct employment potential, so as to cover the three main aspects of sustainability: environmental, economic and social aspects.

Four critical elements are determined: functional unit, system boundary, type of data used and impact assessment methodology.

The functional unit used as a reference for all studied system is 1 m^3 solid over bark (s.o.b.) of woody biomass, delivered to the district heating plant (DHP) of Cavalese (Trento). m^3 solid is a common unit of measure in the forestry sector (Kofman, 2010) and the bark is included (over bark), because valuable for bioenergy.

The system boundary is the alpine forest fuel system shown in Fig. 2. The WTS starts with the logging operation at the forest stand, and ends with energy conversion at the heating plant. Trees are felled with chainsaws at the stump site and extracted with a mobile cable yarder. Once at the yarder landing, trees are delimbed, bucked and stacked by an excavator-mounted processor. Here the logging residues are separated from the round wood and chipped. The wood chips produced from logging residues are transported from the yarder landing to the district heating plant in Cavalese by trucks, and handled by front-end loader.

All forest machines use fossil fuel (diesel).

Instead, in the SWS trees are felled, delimbed and bucked with chainsaws and extracted by cable yarder. Once at the landing, logs are stacked with a loader, often fitted to a tractor.

Emissions, costs and direct employment potential generated from felling and extraction are charged to the total volume of woody biomass (round wood and logging residues) and later prorated, whereas all emissions and costs generated from chipping and chip transport are entirely charged on the energy biomass component. At the heating plant emissions and costs are charged to the total volume of chips consumed by the bioenergy plant of Cavalese in 2008, constituted by both logging residues (tops and branches) and from sawmill residues (slabs, offcuts, slovens).

3. Inventory

3.1. Data collection and assumptions

Reliable data are necessary for quantifying inputs and outputs related to each unit process. Inputs are represented by woody biomass (m^3 s.o.b.), time consumption (h), productivity (m^3 s.o.b./h) and fuel consumption (l/h) (Table 5). Outputs are GHG emissions, costs (euro/m^3 s.o.b.) and direct employment potential (h/m^3 s.o.b.). GHG emissions are symbolized by the global warming potential impact category (kg CO_{2e}/m^3 s.o.b.), where $_e$ means equivalent. According to IPPC (IPCC, 2006), the time horizon for the GWP is 100 years, where the corresponding emissions factors for the calculation of GWP come from IPCC, for the mobile source in the forestry sector (IPCC, 2006). Data concern the years 2008 and 2009. Data regarding cutting volume, stand position etc. are obtained from the Planning Department of the State Forest Administration of Paneveggio (Valle di Fiemme, Trento). Data related to the

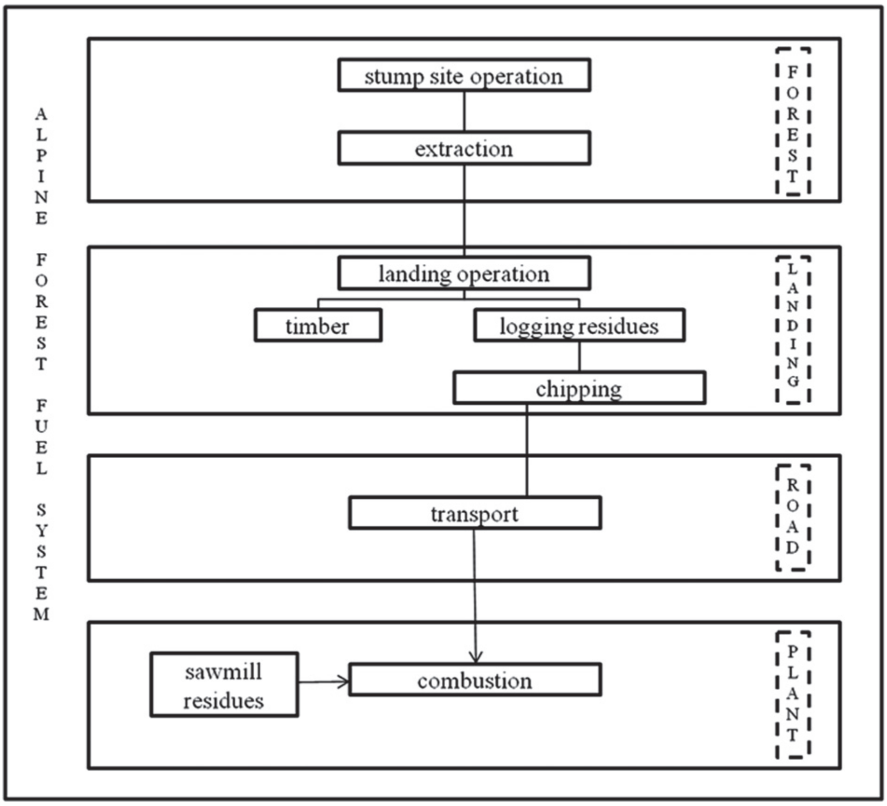


Fig. 2. System boundary of the alpine forest fuel system. Vertical boxes bordered by dotted line represent the operational sites from the forest stand to the end user.

introduction of innovative forest harvesting techniques (mechanized whole tree system) come from previous studies (Spinelli et al., 2008). Data on time consumption for forest machinery come from specific work studies conducted by the authors and published separately (Spinelli et al., 2007, 2008), During these studies, time consumption was measured with the built-in clock of hand-held field computers running the dedicated Siwork 3 software installation (Spinelli and Kofman, 1995). Delays were included in the calculation, since data collection lasted several days and allowed obtaining a reliable representation of delay incidence. Data on fuel consumption and mass output were also measured during the same studies (Piegai, 2000; Spinelli et al., 2007, 2008) or come from the internal records of the State Forest Administration. Data associated with the front-end loader are not included.

Data linked to the silviculture and management of alpine forests are collected at Provincia di Trento, Forest and Fauna Department (Provincia autonoma di Trento, 2010). The biomass plant of Cavalese has provided data about biomass consumption and other management costs (Bioenergia Fiemme, 2010). Data concerning employment potential are derived from the State Forest Administration and from previous studies (Spinelli et al., 2008).

Several assumptions related to woody biomass characteristics, conversion factors for the calculation of biomass volume, energy equivalence (Hellrigl, 2006) and energy content (AIEL, 2009; Hellrigl, 2006) were made, and they are summarized in Table 1. The amount of logging residues was measured as dry tons in previous studies (Spinelli et al., 2006, 2008) and was transformed in m^3 s.o.b. using the recorded data for wood basal density.

Our alpine forest fuel system is assumed to be CO_2 neutral, i.e. it does not increase the CO_2 level into the air (the CO_2 emitted during the combustion of the wood fuels is taken up during the growth of the forest) see e.g. (European Commission, 2007; PAS, 2008). This concept is the base for calculating the GHG benefits of our wood fuel system assumed to replace fossil fuels as fuel oil and natural gas at the DHP. However, the alpine fuel supply chain cannot be assumed completely CO_2 neutral, due to the use of fossil fuels along the supply chain (Schlamadinger et al., 1997).

According to the mentioned assumption of CO_2 neutrality, only CH_4 and N_2O emissions are considered during the combustion process. The value assumed for calculating the emissions from a wood-fired heating plant comes from Wihersaari (2005). Table 2 shows data related to the DHP of Cavalese.

10% of the wood chips delivered to the DHP is assumed to be constituted by logging residues, while the remaining amount comes from sawmill residues sourced in the area.

Machine rates for harvesting equipment are estimated with conventional costing methods (Miyata, 1980), using 2010 input values, as shown in Table 3. Subsidies are not taken into account. Machine rates were divided by productivity figures, in order to estimate unit harvesting cost (euro/m^3 s.o.b.).

Table 1
Assumptions for woody biomass characteristics, conversion factors, energy equivalence and energy content of different fuel.

Woody biomass characteristics	
Density of both round wood and biomass	715 kg/m^3 s.o.b.
Moisture content (wet base)	45%
Biomass expansion factor	Additional 0.26 m^3 equivalent of biomass per m^3 s.o.b. of round wood.
Conversion factor and energy equivalence	
Wood chips	1 m^3 s.o.b. is equal to 2.75 m^3 loose volume
Energy equivalence	1000 l of fuel oil correspond to 14 m^3 wood chips
Energy content	1000 m^3 natural gas at 20 °C and 1 atm pressure correspond to 15.9 m^3 loose volume Round wood and biomass: 9.08 MJ/kg at 45% moisture content Fuel oil: 41 MJ/kg Natural gas: 36 MJ/kg

Table 2
Data related to transportation and management of the DHP in Cavalese.

Transportation to DHP	
Distance to the forest stand	30 km
Loading capacity of trucks	6.3 ton dry matter chips
Cavalese DHP	
Wood chips consumed in 2008	13,709 m^3 s.o.b.
Heat production	28 GWh
Number of bio-boiler	2
Number of rescue boiler based on natural gas	2
Emissions from combustion (CH_4, N_2O)	2 kg CO_{2e}/MWh chip

3.2. Calculation

The GHG emissions have been calculated using the following formulas:

$$\text{fuel consumption (TJ)} > * \text{ emission factor (kg/TJ)},$$

where fuel is calculated as

$$\text{fuel} \left(\text{l}\right) * \text{density fuel}\left(\text{kg/l}\right) * \text{Net calorific value}\left(\text{TJ/Gg}\right) \Big/ 10^6$$

The fuel used in the forest operations is diesel. Data related to these formulas are presented in Table 4. The fuel consumption per functional unit is calculated beginning from productivity data. Productivity figures come from field studies and are representative of actual commercial operations. They are calculated as volume output (m^3 s.o.b.) divided time input (hours, including delays). At the DHP of Cavalese, it is calculated the GHG benefit of replacing fossil fuels (natural gas and fuel oil plant) by our wood fuel system. The CO_2 emissions from the alpine fuel supply chain are taken into account together with CH_4 and N_2O generated both from supply chain and combustion. The GHG benefits are calculated as difference between the emissions from our alpine forest fuel system and the above mentioned reference systems based on fossil fuels. The costs are calculated as the sum between operating costs and profit and overheads. The operating costs are equal to the sum of hourly fixed costs and hourly variable costs. The above mentioned costs derive by calculation from base data presented in Table 3.

The direct employment potential is equal to the ratio between hour (h) and total woody biomass (m^3 s.o.b.).

Table 3
Base components for cost estimation.

Machine	Type	Chainsaw	Yarder	Processor	Chipper	Truck
Purchase price	euro	700	150,000	200,000	320,000	110,000
Economic life	years	2	8	8	7	5
Recovery value	%	0	20	20	20	20
Interest rate	%	4	4	4	6	6
Fuel cost	euro/l	1.4	1.2	1.2	1.2	1.2
Crew	number	1	3	1	1	1
Depreciation	euro/year	350	15,000	20,000	36,571	17,600
Annual use	h/year	1000	1000	1000	1200	1200
Repair and maintenance	%	120	80	60	60	35
Personnel cost[a]	euro/h	21	21	21	21	21
Total fixed cost	euro/h	0.4	23	30	48	14
Total variable cost	euro/h	23	82	55	89	38
Overhead	%	20	20	20	25	25
Total cost	euro/h	28	125	102	171	65

[a] Current national contract for this worker category.

Table 4
Elements for calculating GWP.

	Emissions factor (kg/TJ)	GWP (100 years)
CO_2	74,100	1
CH_4	4.15	25
N_2O	28.6	298
	Density (kg/l)	Net calorific value (TJ/Gg)
Diesel	0.8439	43

Table 6
GWP (kg CO_{2e}/m^3 s.o.b.) and costs (euro/m^3 s.o.b.) for the alpine forest fuel supply chain.

	GWP (kg CO_{2e}/m^3 s.o.b.)	Costs (euro/m^3 s.o.b.)
Stump site op.	0.10	2.38
Extraction	1.25	13.06
Landing op.	3.02	7.32
Chipping	5.29	10.07
Transport	3.54	8.51

3.3. Further analyses

3.3.1. Energy balance

Energy use is estimated as kWh/m^3 s.o.b.

The following equation (Ayres, 1978; Hohle, 2010) was used for calculating the energy balance (input–output ratio) of the assortments used for energy production (logging residues):

$$IE = Fc \times Ec/OE$$

IE is the energy input ratio and it is calculated in percentage. Fc is the fuel consumption of forest machineries in l/m^3 s.o.b., while Ec is the energy content of fuel in kWh divided by OE or the energy output, i.e. the amount of energy released burning wood chips at the combustion plant. The unit of measure for energy input and energy output is kWh, because related to the power of the DHP.

The energy content of 1 l of chainsaw fuel and diesel are respectively 9.1 kWh and 10.1 kWh. The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the DHP of Cavalese.

3.3.2. System comparisons

A comparison between WTS and SWS concerning GWP, costs and direct employment potential was performed for stump site, extraction and landing operations (op.). In the traditional system the harvest of logging residues is excluded. Inputs, as mentioned above, related to both systems are illustrated in Table 5.

3.4. Sensitivity analysis

A sensitivity analysis was conducted in order to gauge the variation of emission levels and production costs as a function of increments or reductions in fuel consumption (l/h) and logging costs (euro/h). Two different levels were considered both for reductions and increments, respectively 10% and 20% below and above the average reference values.

4. Results and discussion

4.1. Environmental and financial analysis

The total GWP of the product supply chain was 13.2 kg CO_{2e}/m^3 s.o.b. (Table 6), including all work steps from the stump site to the arrival at the heating plant. Chipping was the process step with the largest GWP, i.e. 40% of overall emissions (5.29 kg CO_{2e}/m^3 s.o.b.). Transportation came second, contributing 27% of the total GWP (3.54 kg CO_{2e}/m^3 s.o.b.). The remaining kg CO_{2e} was divided between felling, extraction and landing operation, respectively with 1%, (0.10 kg CO_{2e}/m^3 s.o.b.), 9% (1.25 kg CO_{2e}/m^3 s.o.b.) and 23% (3.02 kg CO_{2e}/m^3 s.o.b.) of the total GWP. The product supply chain had an overall costs of 42 euro/m^3 s.o.b., where extraction by yarder was the most expensive operation, accounting for 31% of the total costs (13 euro/m^3 s.o.b.). Chipping came second with 25% (10 euro/m^3 s.o.b.), and transport third, with 21% (8 euro/m^3 s.o.b.). The remaining costs were shared between felling (17% or 7 euro/m^3 s.o.b.) and processing at the landing (6% or 2 euro/m^3 s.o.b.). According to Van Belle (2006) during chipping each single variable can strongly influence the level of CO_2 emissions. Therefore, it is important to consider the technical measures capable of reducing fuel consumption, and consequent emissions. Yarder extraction is the most expensive process, even if it is still economically viable when the slope gradient exceeds 35% and no other techniques are applicable (Heinimann, 2004). Furthermore, cable yarder offers the benefit of environmentally friendly extraction, with limited impacts on the environment, forest soil and the residual stand (Stampfer et al., 2006; Visser and Stampfer, 1998). Cable yarder has already been used in bioenergy supply in Italian mountain areas (Zimbalatti and Proto, 2009). Recent studies showed that between 85% and 95% of the theoretical potential of forest residues can be harvested by yarder in Trentino (Zambelli et al., 2010). At present, local energy plants mostly use sawmill residues, while the amount of forest fuel is still small due to difficulties encountered when harvesting forest residues in steep terrain, and the resulting high supply costs (Secknus, 2007). Other authors have already pointed out the high cost of harvesting mountain forests and the consequent trend to disregard active forest management (Brang et al., 2002). However, since 2006, the State Forest Administration in Paneveggio has recorded a steady increase in the productivity of forest stands by introducing the recovery and chipping of forest residues. This innovation has not resulted in any increase in the harvesting cost of conventional products. Hence, direct experience by the State Forest Administration seems to corroborate our hypothesis, regarding the financial benefit of wood chip utilization for energy purposes. Hence, there is a strong interest in expanding the utilization of forest residues, which would help stabilizing the market of wood chips. In turn, that would require improving the

Table 5
Comparisons of woody biomass, time consumption, productivity and fuel consumption of whole tree system (WTS) and short wood system (SWS).

	Woody biomass (m^3 s.o.b.)		Time consumption (h)		Productivity (m^3 s.o.b./h)		Fuel consumption (l/h)	
	WTS	SWS	WTS	SWS	WTS	SWS	WTS	SWS
Stump site op.	6966	6966	592	1321	11.76	5.27	0.4	0.4
Extraction	6966	6966	728	938	9.57	7.42	4	5
Landing op.	6966	6966	500	711	13.92	9.79	14	8
Chipping	1442	–	85	–	17.03	–	30	–
Transport	1442	–	189	–	7.63	–	9	–

quality of forest chips and developing the forest road network. Short transportation distances between the forest area and the DHP of Cavalese also allowed reduced transportation costs, ultimately achieving positive net income (Hamelinck et al., 2005).

However, WTS allows integration of the recovery of logging residue with the extraction of conventional timber assortments, helping to reduce the costs of both operations, as already stated long ago within the International Energy Agency circle (Hohle, 2010; Hudson, 1995) and confirmed in our study. In the last decade the price trend of wood chips sold as by-products from sawmills to the DHP of Cavalese has increased exponentially, which highlights the urgent economic interest in finding and utilizing wood chips from alternative sources, such as forest residues.

For a GHG point of view, the benefit of using wood fuel is clear at the DHP. Fig. 3 shows the GHG emitted by our wood fuel system compared to two reference systems based on fossil fuel (fuel oil and natural gas plant). In a heating plant, the use of woody biomass allows to avoid 2.3 ton CO_{2e} (169 kg CO_{2e}/m^3 s.o.b.) or 1.7 ton CO_{2e} (122 kg CO_{2e}/m^3 s.o.b.) if replacing fuel oil and natural gas respectively.

4.2. Energy balance

The results for energy use of the WST system are shown in Fig. 4. Each slice in the pie chart represents the amount of kWh/m^3 s.o.b. used by each process step in the years 2008 and 2009. Chipping is the process with the highest energy use in the observed alpine supply chain, explaining the high GWP presented above. The high fuel and energy use of this operation is compensated by its high productivity.

The energy input–output ratio for the supply of logging residue for energy use is 4.9%, meaning that 20 units of wood energy fuel are produced per unit of energy based on fossil fuel consumed. This low energy ratio for fuel chip production is confirmed by previous Nordic studies, see e.g. Wihersaari (2005). The low amount of energy required for tapping the forest fuel resource and the replacement of fossil fuel at a systemic level are crucial advantages of the alpine forest fuel system.

4.3. System comparisons and direct employment potential

The comparative analysis between the traditional (SWS) and innovative (WTS) logging system demonstrates the advantage of using the WTS when trying to curtail emissions and costs (Table 7). In general, WTS incurs higher hourly fuel consumption than SWS, but also offers higher productivity. As a result, the specific fuel consumption per product unit is lower for the WTS, compared to the SWS. Opting for WTS allows a saving of 1.79 kg $CO2_e/m^3$ s.o.b. and 12.17 euro/m^3 s.o.b. In contrast, SWS harvesting has a larger direct employment potential.

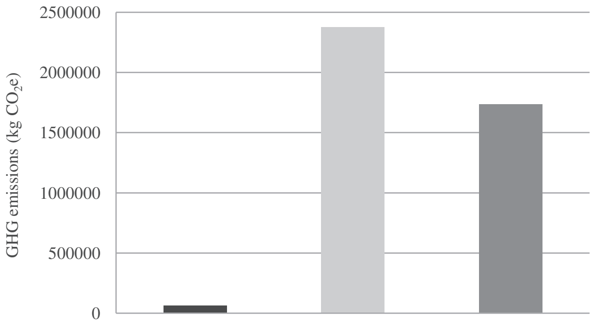


Fig. 3. GHG emitted by our alpine forest fuel supply chain, including emissions from combustion, in comparison to two reference systems based on fossil fuel (fuel oil and natural gas plant).

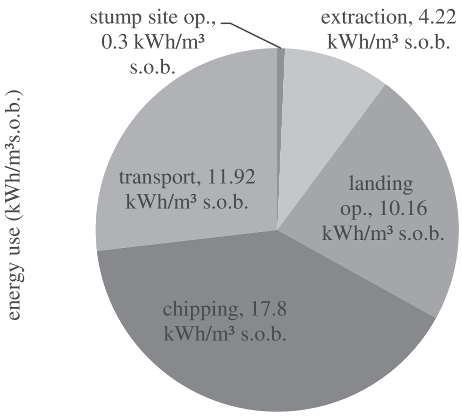


Fig. 4. Energy use (kWh/m^3 s.o.b.) of each unit process in the years 2008 and 2009.

The transportation of logging residues after WTS harvesting generates the highest potential for direct employment, followed by extraction. Regarding the comparison between WTS and SWS, WTS seems to offer greater environmental and financial benefits, although its direct employment potential is a key point to discuss. SWS creates more jobs compared to the WTS as far as the harvesting of conventional round wood is concerned. However, since SWS offers little opportunities for biomass production, it misses all the job potential related to the biomass supply chain. Furthermore, one may wonder if the employment potential is really an issue in logging operations, which seem to attract fewer and fewer people, regardless of availability. Logging is experiencing a severe shortage of qualified labor, and for this reason it seems better to allocate the few available resources to the more productive WTS (Spinelli et al., 2001).

4.4. Sensitivity analysis

A sensitivity analysis was performed for estimating the impact of the key parameters fuel consumption (l/h) and labor cost (euro/h) on total GWP and cost levels. The relative variations in the GWP and labor costs with respect to the base case are presented in Table 8: these correspond to the effect of 10% and 20% increase and decrease in the value of the reference key parameters.

The sensitivity analysis shows that the most sensitive parameter to variations in fuel consumption is chipping. A reduction of 20% in the fuel consumption causes a reduction of 1.05 kg CO_{2e}/m^3 s.o.b., while an increment of 20% results in an increase of 1.07 kg CO_{2e}/m^3 s.o.b. 10% increase or decrease in fuel consumption causes additional 0.55 kg CO_{2e}/m^3 s.o.b. or a reduction of 0.52 kg CO_{2e}/m^3 s.o.b.,

Table 7
Comparison of GWP, costs and direct employment potential[a] between WTS and SWS.

	GWP (kg CO_{2e}/ m^3 s.o.b.)		Costs (euro/m^3 s.o.b.)		D.e.p. (h/m^3 s.o.b.)	
	WTS	SWS	WTS	SWS	WTS	SWS
Stump site op.	0.10	0.23	2.38	10.00	0.08	0.19
Extraction	1.25	2.02	13.06	20.43	0.10	0.13
Landing op.	3.02	4.29	7.32	5.39	0.07	0.10
Total	4.37	6.54	22.76	35.83	0.25	0.42

[a] d.e.p.: direct employment potential.

Table 8
Sensitivity analyses: variation of GWP and production costs achieved in the base case (base), increasing and decreasing fuel consumption and labor cost of 10% and 20% of each operation one at a time.

	GWP (kg CO_{2e}/m^3 s.o.b.)					Costs (euro/m^3 s.o.b.)				
	Base	−20%	−10%	10%	20%	Base	−20%	−10%	10%	20%
Stump site op.	0.1	0.08	0.09	0.1	0.12	2.38	1.87	2.12	2.63	2.89
Extraction	1.25	1	1.13	1.38	1.5	13.06	10.45	11.7	14.32	15.67
Landing op.	3.02	2.41	2.71	3.32	3.62	7.32	5.88	6.6	8.04	8.75
Chipping	5.29	4.24	4.77	5.84	6.36	10.07	8.07	9.07	11.07	12.09
Transport	3.54	2.79	3.18	3.89	3.89	8.51	6.81	7.66	9.37	10.22

respectively. Transport is also a sensitive process step: a reduction of 20% in fuel consumption reduces GWP by 0.75 kg CO_{2e}/m^3 s.o.b., while an increment of 20% generates additional 0.35 kg CO_{2e}/m^3 s.o.b. At the landing, a decrease of 0.61 kg CO_{2e}/m^3 s.o.b. and an increment of 0.6 kg CO_{2e}/m^3 s.o.b. of the GWP are respectively associated to a 20% decrease and a 20% increase in the fuel consumption. The same 10% variation in fuel consumption causes a GWP increase or decrease in the order of 0.30 kg CO_{2e}/m^3 s.o.b. from landing operations.

Extraction was the most sensitive parameter to variations in labor cost. A reduction or increment of 20% in labor cost induces a 2.61 euro/m^3 s.o.b. reduction or increment of the total supply costs. Similarly, a 10% reduction or increase in labor cost causes respectively a reduction of 1.36 euro/m^3 s.o.b., or an increase of 1.26 euro/m^3 s.o.b. of the extraction costs in the base scenario. Chipping is also a sensitive parameter. A decrease of 20% in labor cost generates savings for 2 euro/m^3 s.o.b. in chipping costs. In contrast, an increment of 20% in labor cost results in a cost increase of 2.02 euro/m^3 s.o.b. The same 20% increase or decrease in labor cost cause a parallel increase or decrease of transportation cost equal to 1.71 and 1.70 euro/m^3 s.o.b., respectively.

In conclusions, the sensitivity analyses show that chipping is most sensitive to changes in fuel consumption and extraction to changes in labor cost, as these operations are respectively the most intense users of fuel and labor. In contrast, stump site operations and landing operations are relatively insensitive to variations in fuel consumption and labor cost.

4.5. Sustainability

Different assumptions can strongly influence the results. Furthermore, the harvesting of forest residues may have long-term effects on soil fertility, raising important questions about its sustainability. Since impacts on fertility will vary depending on site conditions, these questions must be addressed on a case by case basis. When implementing the new forest energy supply system, it is important to simultaneously consider all the ecological, economic and social aspects. In addition, in the study area it is important to preserve the esthetic value of the mountain forests, while exploiting the forest for timber production in a sustainable way. A combined analysis of environmental and socio-economic impacts is a good option for carrying out a LCA (Kniel et al., 1996) and for decision makers, that need to find a sustainable solution to environmental problems (Ness et al., 2007). A complete assessment of sustainability requires gauging the effects on soil carbon storage, land use change and biodiversity impacts, consequences on the local economy and on the society. Several studies deal with the introduction of land use change and biodiversity in the LCA (Cherubini et al., 2009; Lindeijer, 2000), although there are still no international standard and common agreements within the LCA field. However, recent studies may provide some comfort, as they have shown the principle feasibility of creating a sustainable forest fuel system in the Italian mountains (Freppaz et al., 2004).

5. Conclusions

The study analyzes the possible exploitation of woody biomass resources for energy in an alpine context. The purpose of the study was to utilize life cycle assessment as a tool for examining the environmental, economic and social impacts in terms of GHG emissions, financial costs and direct employment potential respectively, in an alpine forest fuel supply chain from the forest stand to the DHP. Our case study demonstrates that mountain forests are a viable source of wood fuel, which can be exploited without generating excessive impacts. From the environmental viewpoint, cable yarder is most compatible with the sustainable management of alpine mountain forests. However, the sensitivity analysis indicates that traditional cable extraction is a costly process. Suggested innovations allow reducing both GHG emissions and costs, while offering an affordable bioenergy feedstock. At the same time, the use of local biomass by a local DHP generates a “green” profile of the local community. However, the GWP contribution of each unit process in the supply chain is significant, especially for chipping operation: all along the supply chain one might resort to better technologies, more efficient machines and innovative of biofuels to achieve a radical reduction of GHG emissions (Neupane et al., 2010). The direct employment potential of the suggested innovation needs further analysis: if the innovative system may reduce employment needs in the conventional logging component of the supply chain, it also generates new business and employment through the collateral biomass opportunity. Furthermore, one also needs to consider the current difficulty in recruiting new loggers: in its light, increasing logging labor needs may represent a problem more than a real advantage. An integrated harvesting system based on mechanical equipment and designed to produce both conventional wood products and energy biomass will reduce labor needs, but at the same time may stimulate the forest sector and generate further income for both forest owners and logging companies.

Acknowledgments

The authors gratefully acknowledge the support of the Planning Department of the State Forest Administration of Paneveggio (Valle di Fiemme, Trento), The Forest and Fauna Department of the Provincia di Trento, and the Management of the district heating plant in Cavalese (Trento). We thank you Jos Milner for English revision.

References

AIEL, 2009. Legna e cippato. Produzione, requisiti e compravendita. Associazione Italiana Energie Agroforestali, Legnaro (PD), Italy.
Athanassiadis, D., 2000. Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. Science of the Total Environment 255 (1–3), 135–143.
Ayres, R.U., 1978. Resources, Environment, and Economics: Applications of the Materials/Energy Balance Principle. New York, New York, USA.
Berg, S., 1997. Some aspects of LCA in the analysis of forestry operations. Journal of Cleaner Production 5 (3), 211–217.

Berg, S., Karjalainen, T., 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry 76 (3), 271–284.

Berg, S., Lindholm, E.-L., 2005. Energy use and environmental impacts of forest operations in Sweden. Journal of Cleaner Production 13 (1), 33–42.

Bioenergia Fiemme, 2010. Cavalese, Trento, Italia. http://www.bioenergiafiemme.it/home.

Brang, P., Courbaud, B., Fischer, A., Kissling-Näf, I., Pettenella, D., Schönenberger, W., Spörk, J., Grimm, V., 2002. Developing indicators for the sustainable management of mountain forests using a modelling approach. Forest Policy and Economics 4 (2), 113–123.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resources, Conservation and Recycling 53 (8), 434–447.

Diaci, J., 2006. Nature Based Forestry in Central Europe – Alternatives to Industrial Forestry and Strict Preservation. Ljubljana, Slovenia.

European Commission, 2007. Commission decision of 18 July 2007 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council (notified under document number C(2007) 3416) (2007/589/EC) July 2007.

European Union, 2009. Directive 2009/28/EC of the European Parlament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (23 April 2009).

Finnveden, G., Moberg, Å, 2005. Environmental systems analysis tools – an overview. Journal of Cleaner Production 13 (12), 1165–1173.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., Taramasso, A., 2004. Optimizing forest biomass exploitation for energy supply at a regional level. Biomass and Bioenergy 26 (1), 15–25.

Giovannini, G., 2004. Il comparto delle imprese di utilizzazione forestale in provincia autonoma di Trento. Dendronatura 2, 47–56.

Glavic, P., Lukman, R., 2007. Review of sustainability terms and their definitions. Journal of Cleaner Production 15 (18), 1875–1885.

González-García, S., Berg, S., Feijoo, G., Moreira, M., 2009. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. International Journal of Life Cycle Assessment 14 (4), 340–353.

Hamelinck, C.N., Suurs, R.A.A., Faaij, A.P.C., 2005. International bioenergy transport costs and energy balance. Biomass and Bioenergy 29 (2), 114–134.

Heinimann, H.R., 2004. HARVESTING: forest operations under mountainous conditions. In: Jeffery, B. (Ed.), Encyclopedia of Forest Sciences. Elsevier, Oxford, pp. 279–285.

Hellrigl, B., 2006. Elementi di xiloenergetica. (Elements of wood energy). AIEL, Associazione Italiana Energie Agroforestali, Legnaro (PD), Italy.

Hohle, A.M.E., 2010. Energy consumption by energy wood supply. OSCAR Conference in Forest Operations Research in the Nordic Baltic Region, October 20–22, 2010, Honne, Norway.

Hudson, J.B., 1995. Integrated harvesting systems. Biomass and Bioenergy 9 (1–5), 141–151.

International Energy Agency, 2007. IEA bioenergy 28th update. Biomass and Bioenergy 31 (5), I–XI.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. Agriculture, Forestry and Other Land Use. Intergovernmental Panel of Climate Change, Japan.

ISO, 2006a. International Organization for Standardization ISO 14040: 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO, 2006b. International Organization for Standardization ISO 14044: 2006. EnvironmentalManagement – Life Cycle Assessment – Requirements and Guidelines.

Karjalainen, T., Asikainen, A., 1996. Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 69 (3), 215–228.

Kniel, G.E., Delmarco, K., Petrie, J.G., 1996. Life cycle assessment applied to process design: environmental and economic analysis and optimization of a nitric acid plant. Environmental Progress 15 (4), 221–228.

Kofman, P.D., 2010. Units, Conversion Factors and Formulae for Wood for Energy. Harvesting/Transportation n.21. COFORD, Dublin, Ireland.

Lindeijer, E., 2000. Biodiversity and life support impacts of land use in LCA. Journal of Cleaner Production 8 (4), 313–319.

Miyata, E.S., 1980. Determining fixed and operating costs of logging equipment. USDA Forest Service Technical Report, San Paul, USA.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecological Economics 60 (3), 498–508.

Neupane, B., Halog, A., Dhungel, S., 2010. Attributional life cycle assessment of woodchips for bioethanol production. Journal of Cleaner Production 19 (6–7), 733–741.

PAS, 2008. Publicly Available Specification 2050. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. BSI British Standards, London, ISBN 978 0 580 50978 0. 2008. 29 October 2008.

Piegai, F., 2000. I consumi di combustibile nei lavori forestali. Sherwood 62, 31–32.

Piussi, P., 1994. Selvicoltura generale. UTET, Torino, Italia.

Provincia autonoma di Trento, 2009. Linee guida per il governo del territorio forestale e montano, dei corsi d'acqua e delle aree protette. Dipartimento Risorse forestali e montane, Trento, Italia.

Provincia autonoma di Trento, 2010. Provincia Autonoma di Trento, servizio foresta e fauna. Trento, Italia. http://www.foreste.provincia.tn.it.

Schlamadinger, B., Apps, M., Bohlin, F., Gustavsson, L., Jungmeier, G., Marland, G., Pingoud, K., Savolainen, I., 1997. Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass and Bioenergy 13 (6), 359–375.

Schwaiger, H., Zimmer, B., 2001. A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. In: Karjalainen, T.Z.B., Berg, S., Welling, J., Schwaiger, H., Finér, L., Cortijo, P. (Eds.), Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products — Achievements of the Working Group 1 of the COST Action E9. European Forest Institute (EFI), Joensuu (Finland).

Secknus, M., 2007. Biomass availability, markets and role of associations. Guidelines for the development of a forest chips supply chain model. Filo' srl, pp. 44–58.

Sonne, E., 2006. Greenhouse gas emissions from forestry operations. Journal of Environmental Quality 35 (4), 1439–1450.

Spinelli, R., Owende, P., Ward, S., 2001. A model for estimating the productivity and cost of mechanized harvesting–debarking process in fast-growing Eucalyptus globulus plantations. Forest Products Journal 52 (1), 67–77.

Spinelli, R., Nati, C., Magagnotti, N., 2006. Recupero di biomassa: alcune utilizzazioni in boschi alpini. Sherwood 119, 1–7.

Spinelli, R., Nati, C., Magagnotti, N., 2007. Recovering logging residue: experiences from the Italian Eastern Alps. Croatian Journal of Forest Engineering 28, 1–9.

Spinelli, R., Magagnotti, N., Dellagiacoma, F., 2008. Meccanizzazione nelle fustaie alpine. Due diversi sistemi di lavoro Sherwood 147, 45–49.

Spinelli, R., Kofman, P., 1995. Cantieri agricoli e forestali, informatizzazione dei rilievi. Macchine e motori agricoli 11, 33–35.

Stampfer, K., Visser, R., Kanzian, C., 2006. Cable corridor installation times for European yarders. International Journal of Forest Engineering 17 (2), 71–77.

United Nations, 1998. Kyoto Protocol to the United Nations framework convention on climate change.

Van Belle, J.-F., 2006. A model to estimate fossil CO_2 emissions during the harvesting of forest residues for energy with an application on the case of chipping. Biomass and Bioenergy 30 (12), 1067–1075.

Visser, R., Stampfer, K., 1998. Cable extraction of harvester-felled thinning: an Austrian case study. Journal of Forest Engineering 1, 39–46.

Wihersaari, M., 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28, 435–443.

Wolynski, A., Zanin, M., Scrinzi, G., 2008. Revisione della pianificazione forestale in Trentino a cinquant'anni dall'adozione della selvicoltura naturalistica. Atti III Congresso Nazionale di Selvicoltura, Taormina, Italia.

Zambelli, P., Lora, C., Ciolli, M., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., 2010. A FOSS4G model to estimate forest exploitation methods and biomass availability for renewable energy production. Selected presentations, FOSS4G 2010, Barcelona: OSGEO, Atti FOSS4G 2010, Barcelona, 6-9 September 2010, 1–17.

Zimbalatti, G., Proto, A.R., 2009. Cable logging opportunities for firewood in Calabrian forests. Biosystems Engineering 102 (1), 63–68.

Paper 4

Mountain forests wood fuel supply chains: comparative studies between Norway and Italy

Authors: Clara Valente [1,2], Raffaele Spinelli [3], Bengt Gunnar Hillring [1]

[1] Faculty of Applied Ecology and Agricultural Sciences, Hedmark University College, Anne Evenstadsvei 80, 2480 Koppang, Norway

phone-number: +47-62430846; +47-624308597

e-mail: clara.valente@hihm.no, bengt.hillring@hihm.no

[2] Department of Ecology and Natural resource Management, Norwegian University of Life Sciences. Address: Norwegian University of Life Sciences, Pb.5003 NO-1432, Ås, Norway

[3] CNR IVALSA, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Italy

phone-number: +39-055-5225641

e-mail: spinelli@ivalsa.cnr.it

Corresponding author: Clara Valente

Address: Hedmark University College, Faculty of Applied Ecology and Agricultural Sciences, Evenstad, N-2480 Koppang, Norway

phone-number: +47-62430846

e-mail: clara.valente@hihm.no

Abstract

In Europe, mountain forests constitute more than one quarter of all forested land. Hence, woody biomass from these areas could be an interesting source of raw materials for bioenergy use. Case studies from Norway and Italy are presented and compared in order to determine differences and similarities in mountain forest wood fuel supply chains, where the harvest of logging residues is integrated with conventional timber production. Results from previous studies, where greenhouse gas (GHG) emissions and costs were evaluated using life cycle assessment methodology and cost analysis respectively, are shown and compared. Forest management, harvesting, transportation and combustion at the plant are the processes included in the analysis. Low intensity of forest management characterizes both Norwegian and Italian mountain forests. The Norwegian supply chain is more mechanized than the Italian one. More severe terrain conditions and inappropriate road infrastructure explain partly the persistence of motor manual felling in the Italian case. Mechanized forest harvesting can increase productivity and reduce costs, but it generates more emissions than motor manual harvesting. In both case studies, the main sources of GHG emissions are truck transportation and chipping. Cable yarding in Italy and truck transportation in Norway

incurred the highest costs along the supply chains. Different geographical locations, specific environmental and economic conditions and different drivers behind the consumption of bioenergy make generalization difficult.

Key-words: bioenergy, case studies, harvests, mountainous forests, woody biomass.

Introduction

In Europe, one billion hectares of land are forested which is 36% of the total surface and the rate of growth has increased in the last century (FAO, 2011). Over one quarter of all European forests are mountain forests (Glück, 2002). Reforestation, i.e., reestablishment of forest cover, is occurring especially on sites once used for grazing and agriculture (Piussi, 2000). The functions of mountain forests are many: protection against natural hazards such as avalanches, sources of fresh water, production of goods and services including wood, landscape, recreation, biodiversity conservation etc. (Price, 2003). Mountain forests are also very sensitive to disturbance (Glück, 2002). Due to the altitude, mountain forests normally have a cooler climate compared to lower lying areas and consequently have a different species composition. Slower forest dynamics, regeneration and growth, and low intensity of forest operations characterize mountain forests as opposed to lowland forests (Valente et al., 2011a, Price, 2003). An increment in the global average temperature is predicted by the end of this century (Christensen et al., 2007). This expectation is based on advanced climate modeling which makes it complicated to make short and clear conclusions. However, if the temperature will rise this may determine a shift in the tree line to higher altitudes and increase the availability of wood resources. Nowadays, only 60% of the total forest increment is harvested in Europe and this percentage is even lower in mountain areas (EU, 2009a).

Europe has adopted an energy policy based on reduced carbon emissions. Fossil fuels are being substituted with renewable energy sources in order to achieve the European targets for 2020, i.e. a 20% share of energy from renewable sources and a 20% reduction of greenhouse gas (GHG) emissions (EU, 2009b). Tapping all renewable energy sources is crucial for society to achieve these targets. Woody biomass is one of the renewable energy sources, i.e. naturally replenished. However, one needs to maintain a balance between what the environment can tolerate and what is socio-economically viable, i.e. it must be managed in a sustainable way. In marginal areas, harvesting wood energy can promote rural development (Hillring, 2002) and represents a new source of income for forestry companies.

The International Energy Agency (IEA, 2007) has predicted a 55% increment in energy demand by 2030, compared to 2000 levels. Woody biomass could be one solution for satisfying the increased energy demand, but at the same time there will be more and more pressure to find further sources of wood fuels. Within this context, woody biomass from mountain forests could play a strategic role.

The goal of the study is to present and compare case studies of mountain forest wood fuel supply chains (MFWFSCs) in two contrasting European countries: Norway and Italy. The primary objectives are to identify and explain differences, similarities and dominant trends concerning GHG emissions and costs, as generated by forest management, forest operations, transportation and combustion at the plant. Sensitive elements of each supply chain are highlighted. Furthermore, to strengthen our findings we compared our results with previous literature studies. The secondary objective is to provide empirical evidences of main uncertainties which may occur applying our findings to mountain forests having similar conditions to the ones described in our case studies.

Background

Norway is self-sufficient in energy, with domestic energy consumption being dominated by electricity, mainly based on hydropower (99%). Nowadays, crude oil and natural gas account for almost 50% of the value of all exports (SSB, 2011a). Hence, Norway is involved in fossil fuel businesses alongside the use of hydropower. Consequently bioenergy holds a small share (6%) of the domestic energy consumption (IEA, 2009), of which about 50% is used for heat production by domestic users with small wood stoves. The pellets market for residential areas is very small, close to zero. Productive forests occupy 40% of the Norwegian land, and the annual increment is more than twice the annual harvest (SSB, 2011b). About 30% of the forested area is located in the mountains (Hannerz, 2003), especially in Hedmark and Oppland counties. Norwegian mountain forests are managed according to specific rules, which forbid clear cutting and require the maintenance of the mature forest character (Levende Skog, 2006).

By contrast, Italy is not self-sufficient in energy and domestic energy consumption is mainly based on imported fossil fuels, principally petroleum and gas (77%) (ENEA, 2010). More than 30% of the Italian territory is covered with forests, of which 60% are mountain forests (Croitoru et al., 2005), in particular located in steep terrain. In the last three years Italy has increased its energy production from biomass. As in Norway, wood fuels are mainly used for residential heating. Mountain forests, especially in the Alps, are often integrated into the

Natura 2000 European network, subject to specific rules for the preservation of biodiversity. Selective cutting is the only harvesting system allowed in all Italian forests.

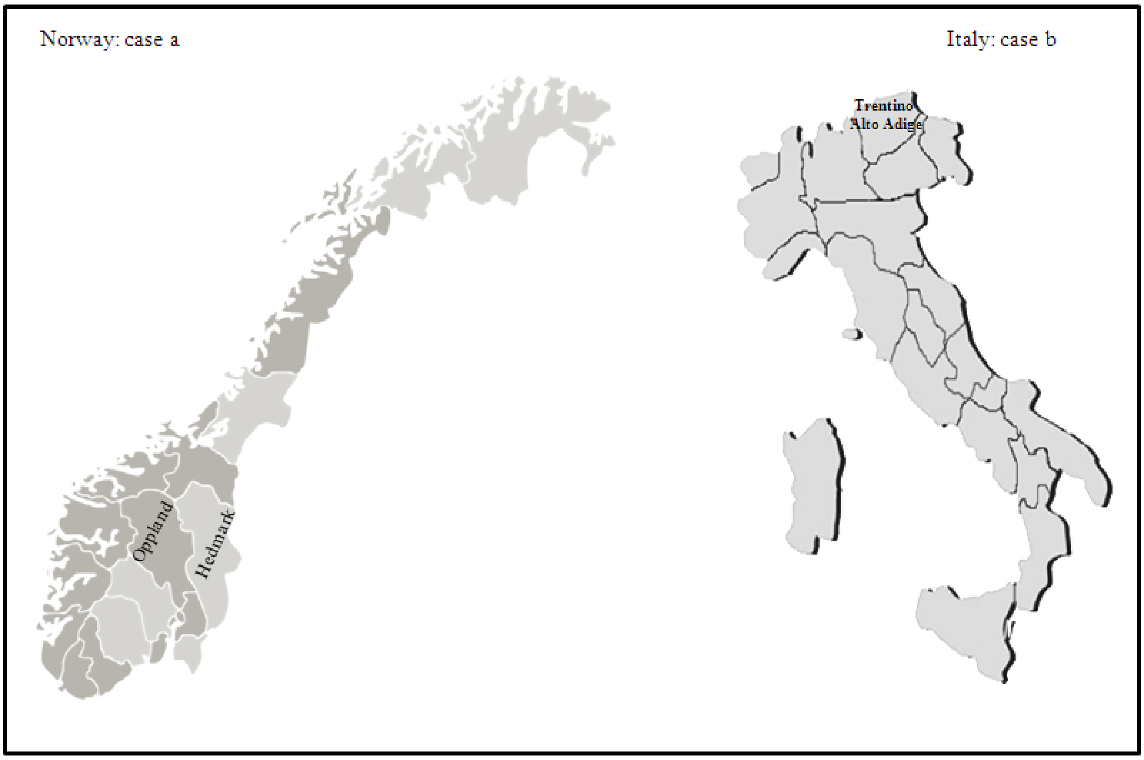
Methods

The research method consisted of a comparative analysis of two case studies: the Norwegian (case a) and Italian (case b) case studies. Both represented existing on-site examples, where theoretical elements have been introduced. The case study technique provides a tool for explorative studies to generate data and knowledge in a new field. The case study formulates the problems and can be supplemented with deeper studies if necessary. It is a debated technique for carrying out scientific analysis, due to the difficulties in formulating generalization (Knight, 2001). However, as an explorative tool, it is commonly used in the literature (Flyvbjerg, 2006), where large amounts and multiple sources of data are not available for describing real and theoretical situations, explaining their interrelations and developing applied solutions (Hirano, 2001). Some examples of case studies performed in the field of bioenergy were found in the literature from all over the world (e.g. Rootzén et al., 2010, Panichelli and Gnansounou, 2008, Dornburg et al., 2005, Van Dam et al., 2009, Gautam et al., 2010, Sevigne et al., 2011, Egeskog et al., 2011, Ozkan et al., 2004, de Jong et al., 2007).

In this study, the mountain forest stands in Hedmark and Oppland counties (South-East of Norway - case a), grew at an altitude of between 700 m and 1000 m a.s.l. in relatively flat terrain and were harvested for 70% of their total standing volume (Valente et al., 2011a). In contrast, mountain forest stands in Fiemme Valley- case b (Valente et al., 2011c) grew at an altitude of between 1500 and 1800 m a.s.l. in steep terrain and had a harvest rate of 35 % to 70% of their total standing volume. Although different conditions of mountain forest stands distinguished case a from case b, vegetation conditions were similar: coniferous species, with Norway spruce [*Picea abies* (L.) Karst.] as the dominant species.

The studied areas in Hedmark and Oppland counties (case a-Norway) and Fiemme Valley-Trentino-Alto Adige region, Trento province (case b-Italy) are shown in figure 1.

Figure 1: Geographical location of case studies: Hedmark and Oppland counties -Norway and Fiemme Valley-Trentino-Alto Adige region, Italy.



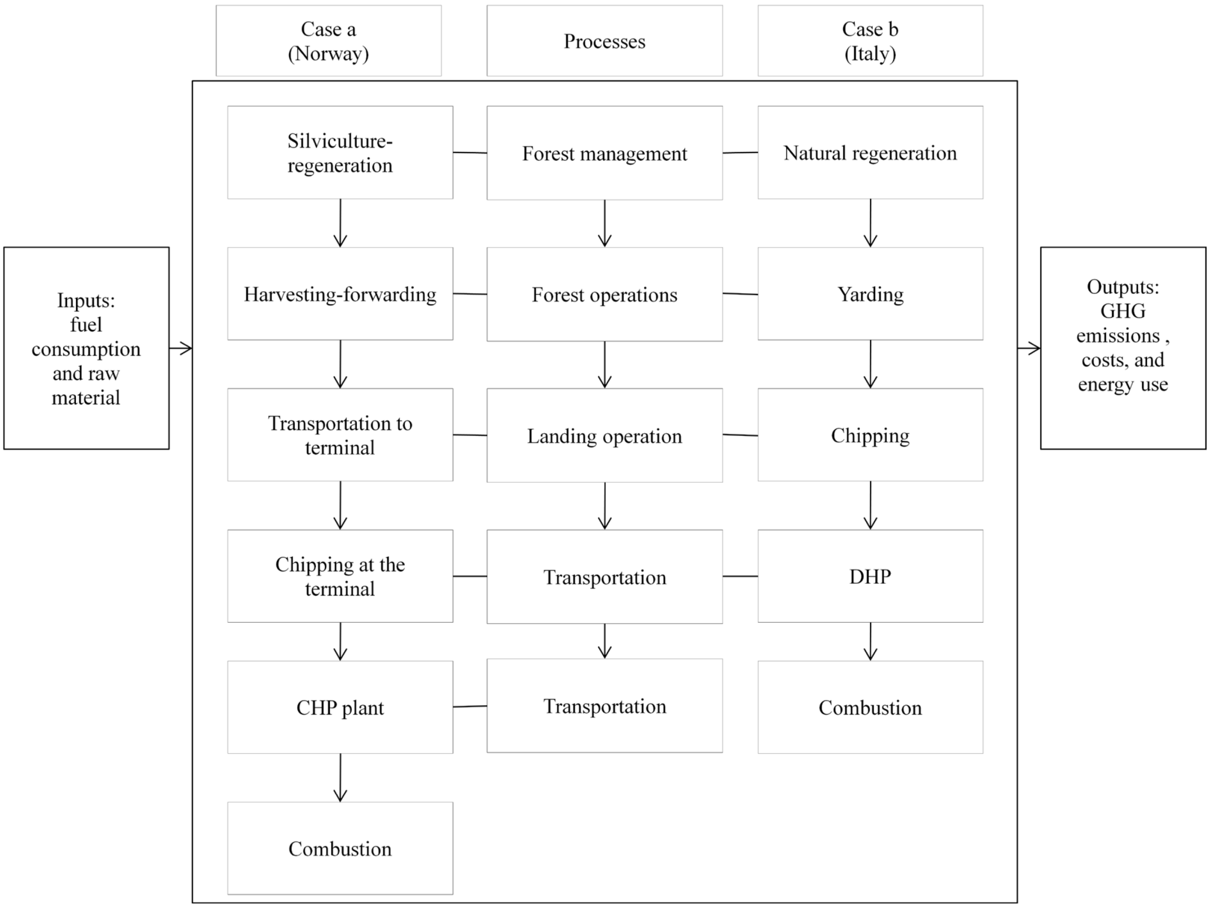
The main method for carrying out our case studies was the life cycle assessment (LCA). LCA is a scientific methodology for assessing the environmental impact of products, in this specific case woody biomass for energy, across the entire life cycle (Baumann, 2004). In both cases, the functional unit used for evaluating system performance was one solid cubic meter over bark (1 m^3 s.o.b.) of woody biomass, harvested and delivered to a combustion plant. This unit is commonly used in forestry, and bark was included because it contributes to energy production (Kofman, 2010). The environmental impact category under assessment was climate change, measured through GHG emissions. The characterization model for GHG emissions was their global warming potential with a time horizon of 100 years (GWP). This was expressed as $kgCO_{2e\ (equivalent)}/m^3$ s.o.b., for CO_2, CH_4 and N_2O emissions. An economic analysis was also performed, based on cost calculations and expressed as €/m^3 s.o.b. The energy use of each unit process was measured in kWh/m^3 s.o.b. Estimated inputs were: the amount of raw materials and fuel consumption. Estimated outputs were: GHG emissions, costs and energy use. The system boundary, illustrated in figure 2, was the entire supply chain, i.e. a network of different unit processes involved from the forest stand to the combustion plant, including forest management, forest harvesting, biomass transportation and processing. In both cases, woody biomass was constituted by round wood and logging residues (tops and branches). Neither below-ground biomass nor stumps were included in these studies. The harvest of logging residues generally left at the forest stands was integrated with the conventional logging operation (harvesting and forwarding in case a, and felling, extracting and processing operations in case b). Results from our previous work (Valente et al., 2011a, Valente et al., 2011b, Valente et al., 2011c) were used for the comparison of MFWFSCs in Norway and Italy.

In case a, artificial regeneration was assumed as the normal practice, obtained through soil scarification and planting. However, the cited operations were rare in mountain forests, and represented a hypothetical case scenario in the Norwegian study. Harvesters and forwarders were used for ground-based logging. Logging residues were separated by round wood, bundled, forwarded to the landing and then transported to the terminal (Valente et al., 2011a). Here, bundles were chipped and loaded into railroad cars for transportation to neighboring Swedish plants, 285 km away. Diesel locomotors were used for the trip to the Swedish border, whereas electric locomotives took over from there to the combined heat and power (CHP) plant (Valente et al., 2011b). In case b, mountain forests were left to natural regeneration, which is the customary practice in Italy. The whole tree system (WTS) was the assumed logging system in the Italian case. Trees were felled by chainsaw and extracted by cable yarder. At the landing, an excavator-mounted processor delimbed, bucked and stacked logs and logging residues separately. Only the latter were chipped at the landing and transported by trucks to a local district heating plant (DHP) 30 km away (Valente et al., 2011c).

An energy balance (input-output ratio) was estimated as the product between fuel consumption and energy content of fuel, divided by the energy output, i.e. amount of energy released during the combustion of wood chips at the heating plant. In both case studies, woody biomass for bioenergy use was assumed to be carbon neutral, implying that the CO_2 released during the combustion process of the wood fuels is sequestered during the growth of the forest. This concept was the base for assessing the GHG benefits of our MFWFSC, where our wood fuel system was assumed to displace fossil fuel at the combustion plants, which otherwise would have been fired with oil, coal or natural gas in case a and fuel oil or natural gas in case b. However, the operations were not completely CO_2 neutral, due to the use of fossil fuels along the supply chains. and the CO_2 emissions of machine operations were added to the emissions of CH_4 and N_2O, originated by both supply and combustion.

Sensitivity analyses were carried out for identifying critical unit process, sensitive to changes, along the studied supply chains. In case a - from the forest stand to the terminal- results for each unit process related to GHG emissions and costs was decreased and increased by 10% one at time for finding out changes smaller or larger than 1.5% compared to the final results (Valente et al., 2011a). Later on, from the terminal to the user, the fuel consumption of each unit process was increased and decreased of 10% and 20% for checking the influence on the energy use (Valente et al., 2011b). In case b, fuel consumption and logging costs were increased and decreased of 10% and 20% for verifying the effect on GHG and cost levels (Valente et al., 2011c).

Figure 2: System boundaries of the Norwegian and Italian mountain forest wood fuel supply chains: case a and b respectively on the left and right side and assessed processes in the centre.



Results and discussion

Table 1 illustrates the results of GWP, operational costs and energy use for each unit process involved in the studied MFWFSCs.

Table 1: GWP, costs and energy use of each unit process considered in Norwegian (case a) and Italian (case b) supply chains

	GWP		costs [a]		energy use	
	$kgCO_{2e}/m^3$ s.o.b.		€/m^3 s.o.b.		kWh/m^3 s.o.b.	
	case a	case b	case a	case b	case a	case b
silviculture	0.04	-	4.50	-	0.16	-
regeneration	0.23	-	10.04	-	0.85	-
logging operations	harvesting	felling	harvesting	felling	harvesting	felling
	3.04	0.10	10.12	2.38	11.33	0.3
	forwarding	extraction	forwarding	extraction	forwarding	extraction
	4.24	1.25	9	13.06	15.81	4.22
	-	processing	-	processing	-	processing
		3.02		7.32		10.16
bundling	4.45	-	11	-	16.59	-
terminal	5.55	-	13.20	-	20.68	-
chipping	3.60	5.29	6	10.07	12.12	17.8
loading	0.75	-	n.a.	-	2.52	-
transport	railway	roadway	n.a.	roadway	railway	roadway
	0.99	3.54		8.51	21.81	11.92
total (rounded off)	22.90	13.20	64	41	102	44

[a] 1 euro=8 NOK; n.a. = not available; – = not included

In the Norwegian case study, the operations with the highest GWP were transportation to the terminal and bundling. In the Italian case study, the highest GWP was generated by chipping at the yarder landing and truck transportation of wood chips to the user plant. In both studies, truck transportation generated the highest emissions along the supply chain, and chipping released about 3 kg CO_{2e}/m^3 s.o.b. The GWP of logging was estimated by summing the emissions of mechanized harvesting and forwarding in case a, and of motor-manual felling, cable yarding and mechanized processing in case b. The resulting GWPs were 7.8 kg CO_{2e}/m^3 s.o.b. and 4.4 kg CO_{2e}/m^3 s.o.b., respectively in case a and b. The logging system adopted in the Norwegian case used 13 kWh/m^3 s.o.b. more than the logging system adopted in the Italian case. In contrast, chipping at the landing (case b) used more energy than chipping at the terminal (case a). The total energy use of the Norwegian supply chain was twice as high as the Italian one. Regardless, the energy balance was very favorable for both systems, and below 5%, i.e. only 5 units of fossil fuel energy input were used to produce 100 units of wood fuel energy output. Railway transportation had a low GWP per ton and km, but a high energy use due to fossil fuel consumption by diesel train.

Figure 3 and figure 4 for case a and b respectively, showed the GHG benefits of replacing fossil fuels with wood fuels at the combustion plant. In case a, the substitution of a coal, oil or natural gas with a wood fuel plant would save 350 kg CO_{2e}/m^3 s.o.b., 165 kg CO_{2e}/m^3 s.o.b. and 156 kg CO_{2e}/m^3 s.o.b. respectively, while in case b the replacement of oil and natural gas would save 165 kg CO_{2e}/m^3 s.o.b and 122 kg CO_{2e}/m^3 s.o.b. respectively. Regarding costs, cable yarding had the highest expenditure, followed by chipping and truck transportation in case b. Truck transportation to the terminal and bundling had the highest expenditures in the first part of the Norwegian supply chain (Valente et al., 2011a). However, costs of transportation by truck and train -from the terminal to the user- were lacking, making more difficult to discuss the results for the whole Norwegian MFWFSC.

Sensitivity analysis illustrates that emission values from transportation by truck and chipping operations, respectively in case a (Valente et al., 2011a) and b (Valente et al., 2011c), were the most sensitive unit processes to changes in the input parameter for fuel consumption. In the Norwegian case, a reduction of 10% in transportation to the terminal causes 2.2% less emissions (Valente et al., 2011a). In Italian case, a reduction of 20% in fuel consumption for of chipping operation caused a decrease of 1.05 kg CO_{2e}/m^3 s.o.b., while an increment of 20% provoked additional 1.07 kg CO_{2e}/m^3 s.o.b. (Valente et al., 2011c). Changes in fuel consumption influenced significantly results in energy use in the second part of the Norwegian supply chain (Valente et al., 2011b). In case a, bundling was a critical process step, in terms of both GWP and costs, even though it gave lower transport costs later in the supply chain. In case b, cable yarding was very sensitive to changes in operational costs. A decrease or increase of 20% in labor cost caused 2.61 €/m^3 s.o.b. decrease or increase in the cost of the overall supply chain (Valente et al., 2011c). In both case studies, transportation by truck and chipping operations were sensitive to changes in cost factors.

Figure 3: GHG balance of the Norwegian case study (case a): GHG emissions of the mountain forest wood fuel supply chain in the positive part of the chart and emissions avoided by the replacement of fossil fuels with wood fuel in the negative part.

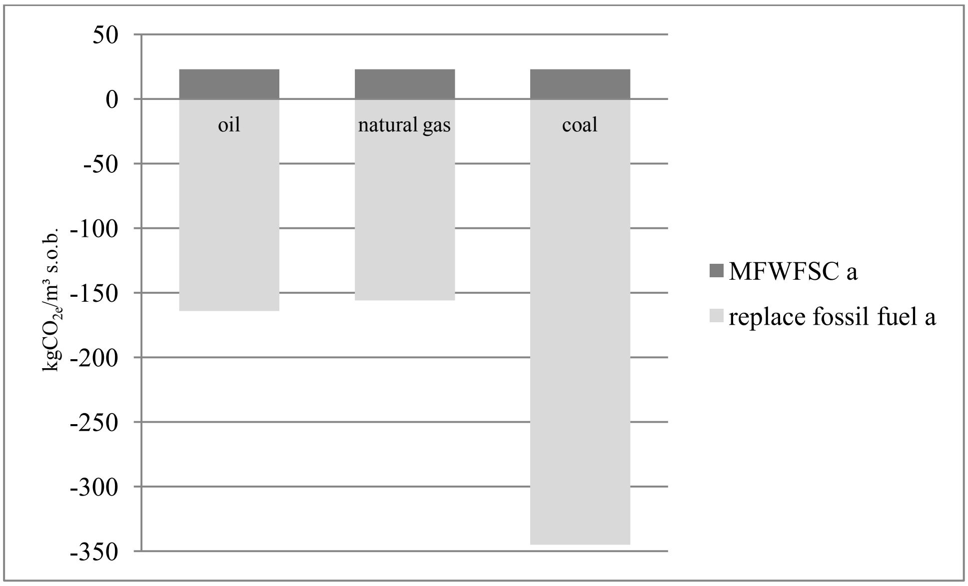
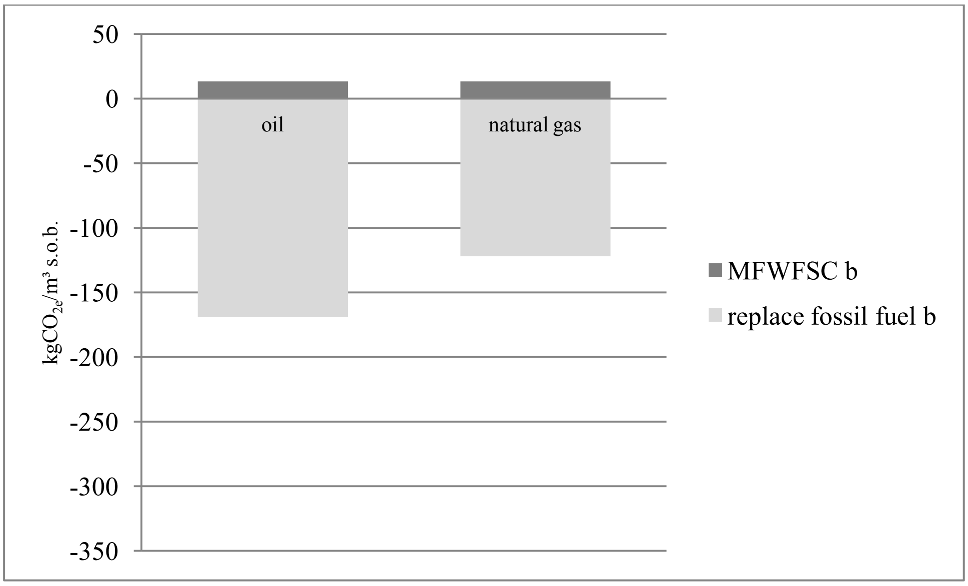


Figure 4: GHG balance of the Italian case study (case b): GHG emissions of the mountain forest wood fuel supply chain in the positive part of the chart and emissions avoided by the replacement of fossil fuels with wood fuel in the negative part.



Low intensity of forest management characterized both Norwegian and Italian mountain forests, mainly left to natural regeneration. In case a, the improvement of the quality of forest stands through soil scarification and planting was rare. In the last 20 years, there has been a significant decrease of registered planting in Norway. The production of seeds adapted to mountain conditions is not feasible at the moment. Regeneration by planting had high labor costs for wood fuel chains, as confirmed by Lindner (2010). Nevertheless, investments in silviculture will help to ensure future production and value creation, as well as environmental protection (Dotta and Motta, 2000, Flæte, 2009). In the Italian case, where wood production is one of the main sources of income for forest owners, it is important to plan forest management that facilitates the socio-economic growth of these areas (Notaro, 2005).

The Norwegian case shows that logging operations were fully mechanized even in mountain areas. Nowadays, harvesters and forwarders are very common in mountain forests. On the contrary, case b showed the permanence of motor-manual felling and extraction in Italian mountain forests. The main reasons were the technical and economic limitations of using harvesters and forwarders in such steep terrain as the studied area. At present, in Trento province, part-time businesses and the small average size of forest companies, low harvesting volume and inappropriate road infrastructure do not give sufficient reasons for purchasing processors. However, in the last years, a widespread use of mechanical processors has been registered, a sign of the growing modernization of Italian forestry (Spinelli et al., 2008). In the 1970s and early 80s motor-manual logging was also common in the Norwegian forests (Vennesland, 2006), and it was gradually replaced in the 1990s by mechanized harvesting, which was more productive, less time demanding and less costly than the motor-manual system due to the high cost of labor and difficulties in worker recruitment in Norway. Nevertheless, the introduction of mechanized harvesting is associated with an increased use of fossil fuel and causes an increment of GHG emissions, which explains why logging operations in the Norwegian study had higher emissions than in the Italian case.

With mechanization in Norway over the last 20 years, the harvest of difficult and steep terrain has declined prominently in mountain areas, as confirmed by our case study in Hedmark and Oppland counties: the only activities concerning mountain forests occurred in highlands that were accessible to harvesters and forwarders, while forests growing in steep terrain were not managed at all. This highlights a substantial difference compared with Trento province (case b). Here, steep slopes prevent ground-based logging, thus limiting the introduction of the classic harvester and forwarder team. Hence, cable yarder, as shown in case b, has a great capacity for working in difficult terrain and generally results in lower logging damage than ground-based logging (Spinelli et al., 2010). Indeed, cable extraction is commonly used in Southern European mountain forests, as emphasized by Zimbalatti and Proto (2009).

In case b, yarding had the lowest GWP impact, but at the same time the largest cost of any process within the MFWFSC. Results of the operational costs in the Italian context confirmed low emissions for extraction (1.5 Kg CO_{2e}/m^3 s.o.b.) but a high cost of installation for cable yarders, as well as low productivity (Di Fulvio, 2010). Traditional motor-manual short wood systems (SWS) incur even higher costs than the innovative whole-tree extraction system (WTS) presented here for case b (Valente et al., 2011c). The cost of extraction was 7 €/m^3 s.o.b. higher in the SWS than in the WTS, because of the less efficient motor-manual tree processing, requiring more time and labor (Spinelli et al., 2008).

In Norway, the use of cable yarders peaked in the 1980s and then dropped off considerably, due to reduced timber prices, difficulties in finding skilled operators, high operational costs, little technical development so far and poor public acceptance (Vennesland, 2006). However, some efforts are being made to bringing back this technique to the Norwegian west coast (Asikainen, 2011). It is interesting to know that in Norway, 49% of forested land has an inclination greater than 20% and most of the potential for increased harvesting is in difficult terrain and low site quality, as is typical of mountain forests (Vennesland, 2006). The authors are aware of the constant development of steep terrain harvesting technology, that can be an alternative to cable yarding such as self-leveling and tethered machines (ECOWOOD, 2001), but at the moment these techniques are too costly, with too high environmental impact and inappropriate to slope of such inclination as Trento province to introduce into our supply chains.

In Norway, logging residues were assumed to be bundled and transported by regular timber trucks to the terminal, where they were chipped. Instead in the Italian case, logging residues were chipped at the landing and then transported to the DHP by chip trucks. Bundling is an effective system and is economically viable for transportation distances longer than 60 km (Kärhä and Vartiamäki, 2006), as shown in case a, because bundles are denser than loose chips and allow building larger payloads (Hakkila, 2004). However, according to Lindholm et al. (2010), bundling forest residues is currently less energy efficient than not bundling and, as case a showed, is expensive because it introduces an additional process step in the supply system. Further studies performed in the Alps (Kanzian and Holzleitner, 2006) and elsewhere Kärhä and Vartiamäki (2006), also highlight the high cost of bundling (7.3 €/m^3 s.o.b. in the Alps), compared to the common system of chipping at the landing (3 €/m^3 s.o.b.). Tests on the use of bundling were actually performed in the Italian Alps (Spinelli and Magagnotti, 2009), including Trentino, corroborating its high cost. In addition, the bundling machine has limited access to forest roads (Spinelli et al., 2007). At any rate, the short transportation distance made bundling unnecessary. However, according to John Deere (Kilponen, 2010), bundlers have a significant market in the mountain areas of Spain and South America, with similar conditions to Scandinavia.

In case a, GWP and costs of energy supply were lower when energy wood was exported to neighboring Sweden, rather than burned locally (Valente et al., 2011b). Here, the longer transportation distance was compensated by the higher efficiency of railway transportation. On the other hand, case b represented the benefits of local use, whereby short transportation distance was a key factor in the reduction of costs, which are anyhow dependent on geographical location (Möller and Nielsen, 2007). At the moment, Italy is a net importer of wood. Technological innovation, including better boiler efficiency, can make local supplies more competitive, as it may allow mechanized wood processing and integrated biomass and round wood harvesting (Giovannini, 2004). In the long run, a more intensive production of wood fuels might make alpine areas increasingly self-sufficient in energy.

In Norway, district heating is scarcely developed, representing only 1% of the total net energy consumption (SSB, 2011a). The low price of electricity (the main source of heat), the scarcity of infrastructure adapted to district heating, the high investment cost of plants and the limited technical development are the main obstacles to the further development of bioenergy in Norway. The high price of wood fuel and high labor costs characterize Norway, compared to other European countries (IEA, 2009). Hence, the limited internal market for bioenergy makes Norway a net exporter of solid biofuels (Junginger et al., 2008), as confirmed by case a.

From a GHG perspective, rail transportation (case a) was preferable to truck transportation, especially over long distances. In this respect, our findings were corroborated by other studies (Tahvanainen and Anttila, 2011, Gustavsson et al., 2011). Rail transportation in Finland e.g. is competitive with road transportation over distances greater than 160 km (Tahvanainen and Anttila, 2011). Furthermore, rail transportation has positive effects on the reduction of CO_2 emissions (Gustavsson et al., 2011). However, at the moment most wood products are transported by truck (Schwaiger and Zimmer, 2001). The cost of transportation by truck is higher in Norway than in other countries, due to stricter road regulations (e.g. smaller vehicle sizes are allowed compared to Sweden), higher fees and poorer roads (Vennesland, 2006).

In Nordic countries, terminals assure the constant delivery of wood chips, by offering storage capacity to buffer any temporary mismatches between demand and supply, and by consolidating more product streams from different sources.
The capacity of CHP plants to accept low-quality fuel, so reaching a higher efficiency of the fuel input, and the superior efficiency of rail transportation make it in this case more effective to export Norwegian biomass to Sweden, than to use it locally (Valente et al., 2011b). Currently biomass for CHP plant and DHP has limited competitiveness in most countries due to the high costs for producing biofuels. But increasing energy prices in general mean it will become more and more profitable in the near future and subsidies have to be introduced to reach the EU targets for renewable energy. On the Swedish side, there have already been strong incentives to invest in bioenergy plants for many years due to heavy taxation of fossil fuels and programs like the green electricity certificates that make it profitable. A different situation was found in Norway, even though, according to Trømborg et al. (2008), forest residues have great potential for bioenergy production in Norway. In the short term, it is predicted that a decrease in the availability of sawmill residues and a parallel increase in their price, will make it necessary to produce wood fuels from forest residues to match the increased demand for bioenergy (Trømborg et al., 2007).
Hence, a combination of harvesting forest residues, chipping at the terminal, railway transportation for long distances and large scale CHP plants may have great potential for development, as shown in other studies (e.g. Forsberg, 2000, Wihersaari, 2005, Tahvanainen and Anttila, 2011).

The Italian system is limited by poorly developed road and rail infrastructure, which affects the technological and technical choices, the appropriate location of terminals and the need for a local end user. In turn that implies a lower need for terminals, which would add cost to the supply chain. Hence, the use of terminals is not so common in Italy, in line with new logistical trends on stock reduction and decentralization. In Alpine areas, chipping at the landing is still the most effective system (Spinelli et al., 2007). However, the productivity of industrial chipping at a terminal is usually higher than achieved at the forest landing (Asikainen, 1998). The location of wood biomass comminution, i.e. the process by which solid materials are reduced in size by chipper, influences the whole supply chain (Allen, 1998, Hakkila, 2004) and is strictly tied to local conditions. In both case studies, chipping was one of the operations with the highest emissions, confirmed by the sensitivity analysis.

However, a significant reduction of CO_2 emissions can be achieved by increasing the diameter of wood fuel fed into the chipper (Van Belle, 2006).

Regarding the energy balance (input-output ratio), the fossil fuel input required in the supply chains for energy output released during the combustion process of wood chips at the plant was low (below 5%), indicating that these chains are energetically attractive, corroborating the results from other studies (Wihersaari, 2005, Eriksson and Gustavsson, 2008, Lindholm et al., 2010). However, all these authors reported an energy input for lowland conditions, slightly lower than case a and b. Energy input was higher in the Norwegian case due to longer transportation distance in case a, compared with short distance in the Italian case, introduction of the bundling operation and comminution at the terminal which increased loading work.

In both case studies, the replacement of fossil fuel with energy wood dramatically reduced GHG emissions, especially when coal (case a) and fuel oil (case b) were replaced. This result is in agreement with Cherubini (2010): substitution of plant based on coal and natural gas have the highest and the lowest GHG saving respectively.

The Italian case study had lower emissions, energy use and costs than the Norwegian case. The main explanation was in a less mechanized and simpler supply chain (more process steps –silviculture, bundling, and terminal- were involved in the Norwegian case). However, discrepancies could also be due to diversity in data availability, data collection and assumptions. Technical choices are connected to the location of mountain forests - steep terrain in Italy versus flatter terrain in Norway.

Concerning the assessment of sustainability, results from ToSIA, a tool for evaluating the sustainability of forest wood chain supply chain (Lindner et al., 2010, Lindner et al., 2011), were comparable with our main findings. For example, low mechanization involves less efficient logging operations, but at the same time higher labor demand and costs.
We should remember that it is important to guarantee the respect of the environment in all its shapes, e.g. preserving biodiversity through sustainable forest management (Klenner et al., 2009). The harvesting of wood biomass from mountain areas will have additional goals than only energy wood production and the introduction of selective cutting for bioenergy

production can create a more natural-looking forest stand, thus achieving an aesthetic goal as well.

Conclusions

In this paper we present two complete case studies of mountain forest wood fuel supply chains in Norway and Italy. We highlighted the main environmental and economic aspects of both chains. Both solutions were closely related to specific geographical, environmental and economic conditions. Different ways of managing the supply chain makes it difficult to draw generalizations. Nevertheless, it is possible to extend our results to conditions similar to those described above. Based on our results, we can conclude that it is realistic to harvest woody biomass, including logging residues, from mountain areas. Energy input-output ratio was similar to previous studies made in lowland conditions. The GHG emissions avoided by the substitution of fossil fuel plant with bioenergy plant were large, especially when wood chips substituted coal and fuel oil.

Intensive harvesting and excessive mechanization can affect the stability of mountain ecosystems, and increase emissions from forestry operations. On the other hand, disregarding the potential contribution of mountain forest can also be harmful. Sourcing energy wood from mountain areas can create new socio-economic opportunities for rural communities, while contributing to self-sufficiency in energy at the local and national level. Technological innovation gives higher productivity and a reduction of internal costs. The sensitivity analysis suggested that fuel consumption was a critical parameter in the GHG emissions of both truck transportation and chipping. Regarding costs, extraction by cable yarder in Italy and transportation by truck in Norway were the most expensive operations. The integration of logging residue harvesting with the conventional logging of round wood improved the efficiency of the supply chains. Low intensity of forest management characterized the sites of both our case studies. An active forest management can improve the quality of forest stands and the availability of woody biomass for bioenergy.

The sustainability of energy systems has become a hot topic in the last years, so ethical questions could and should arise concerning which type of forestry we want for the future in mountain areas. One may question whether it is environmentally and socio-economically sustainable to dedicate specific mountain forest stands for bioenergy production alone.

REFERENCES

ALLEN, J., M. BROWNE, A. HUNTER, J. BOYD AND H. PALMER, 1998. Logistics management and costs of biomass fuel supply,. *International Journal of Physical Distribution and Logistics Management 28 (6), pp. 463–477*.

ASIKAINEN, A. 1998. Chipping terminal logistics. *Scandinavian Journal of Forest Research,* 13**,** 386–391.

ASIKAINEN, A., STAMPFER, K., TALBOT, B. 2011. An evaluation of skyline systems in Norwegian conditions using discrete-event simulation. *In: Ackerman, P.A., Ham, H., & Lu, C. (eds.): Developments in Precision Forestry since 2006, pp. 20-22. Stellenbosch University, Stellenbosch, South Africa, 1-3 March 2010.*: Conference Reports.

BAUMANN, H., TILLMAN, A-M. 2004. *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application* Lund, Sweden, Studentlitteratur.

CHERUBINI, F. 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. *Renewable Energy,* 35**,** 1565-1573.

CHRISTENSEN, J. H., HEWITSON, B. & BUSUIOC, A., CHEN, A., GAO, X., HELD, I., JONES, R., KOLLI, R.K., KWON, W.-T., LAPRISE, R., MAGAÑA RUEDA, V., MEARNS, L., MENÉNDEZ, C.G., RÄISÄNEN, J., RINKE, A., SARR, A. & WHETTON, P. 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change *Regional climate projections.* Cambridge, UK, New York, USA: Cambridge University Press.

CROITORU, L., GATTO, P., MERLO, M. & PAIERO, P. 2005. Italy. *In:* MERLO, M., CROITORU, L. (ed.) *Valuing Mediterranean Forests – Towards Total Economic Value.* Wallingford, Cambridge, UK, 279-298: CABI Publishing

DE JONG, B. H., MASERA, O., OLGUÍN, M. & MARTÍNEZ, R. 2007. Greenhouse gas mitigation potential of combining forest management and bioenergy substitution: A case study from Central Highlands of Michoacan, Mexico. *Forest Ecology and Management,* 242**,** 398-411.

DI FULVIO, F. 2010. *Analysis of small dimater energy- wood harvesting machinery, equipment and systems,* Viterbo, Diss. Department of Technology, Engineering and Science of Environment and Forests University of Tuscia.

DORNBURG, V., TERMEER, G. & FAAIJ, A. P. C. 2005. Economic and greenhouse gas emission analysis of bioenergy production using multi-product crops--case studies for the Netherlands and Poland. *Biomass and Bioenergy,* 28**,** 454-474.

DOTTA, A. & MOTTA, R. 2000. *Boschi di conifere montani - Indirizzi selvicolturali*, Regione Piemonte, Blu edition.

ECOWOOD 2001. *The development of a protocol for ecoefficient wood harvesting on sensitive sites (ECOWOOD). EU fifth framework project on quality of life and management of living resources.,* Dublin, Ireland, Forest Engineering Unit, University College.

EGESKOG, A., BERNDES, G., FREITAS, F., GUSTAFSSON, S. & SPAROVEK, G. 2011. Integrating bioenergy and food production--A case study of combined ethanol and dairy production in Pontal, Brazil. *Energy for Sustainable Development,* 15**,** 8-16.

ENEA 2010. *Rapporto Energia e Ambiente. Analisi e scenari 2009,* Roma, Italia, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile.

ERIKSSON, L.-N. & GUSTAVSSON, L. 2008. Biofuels from stumps and small roundwood--Costs and CO2 benefits. *Biomass and Bioenergy,* 32**,** 897-902.

EU 2009a. *Forestry statistics,* Luxembourg, Eurostat: Publications Office of the European Union.

EU 2009b. *Directive 2009/28/EC of the European Parlament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (23 April 2009).* Official journal of the European Union, L 140, 16-62.

FAO 2011. *State of the World's Forests 2011*, Food and Agricultural Organization.

FLYVBJERG, B. 2006. Five Misunderstandings About Case-Study Research. *Qualitative Inquiry,* 12**,** 219-245.

FLÆTE, P. O. 2009. *Energiforbruk og utslipp fra skogproduksjonskjeden med utgangspunkt i aktivitetsdata fra 2007- fra frø til industritomt. [Energy consumption and emissions from 260 forest production chain based on activity data from 2007 - from seed to timber industry]. (Working paper)* Ås, Norway, Norsk institutt for skog og landskap. (In Norwegian).

FORSBERG, G. 2000. Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method. *Biomass and Bioenergy,* 19**,** 17-30.

GAUTAM, S., PULKKI, R., SHAHI, C. & LEITCH, M. 2010. Economic and energy efficiency of salvaging biomass from wildfire burnt areas for bioenergy production in northwestern Ontario: A case study. *Biomass and Bioenergy,* 34**,** 1562-1572.

GIOVANNINI, G. 2004. Il comparto delle imprese di utilizzazione forestale in provincia autonoma di Trento. *Dendronatura,* 2**,** 47-56.

GLÜCK, P. 2002. Property rights and multipurpose mountain forest management. *Forest Policy and Economics,* 4**,** 125-134.

GUSTAVSSON, L., ERIKSSON, L. & SATHRE, R. 2011. Costs and CO2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. *Applied Energy,* 88**,** 192-197.

HAKKILA, P. 2004. *Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999–2003. Final report,* Helsinki, Finland, 29-49, National Technology Agency of Finland

HANNERZ, M. 2003. Forest research in the north. *Scandinavian Journal of Forest Research. News & Views.,* 4**,** 291-293.

HILLRING, B. 2002. Rural development and bioenergy--experiences from 20 years of development in Sweden. *Biomass and Bioenergy,* 23**,** 443-451.

HIRANO, T. 2001. Methodology for case studies of accidental gas explosions. *Journal of Loss Prevention in the Process Industries,* 14**,** 553-557.

IEA 2007. IEA Bioenergy 28th update. *Biomass and Bioenergy,* 31**,** 1-11.

IEA 2009. *Bioenergy task 40. Sustainable International Bio-energy trade. Country report 2009 for Norway. International Energy Agency* http://www.bioenergytrade.org/downloads/norwegiancountryreport09.pdf Visited on September 2011.

JUNGINGER, M., BOLKESJØ, T., BRADLEY, D., DOLZAN, P., FAAIJ, A., HEINIMÖ, J., HEKTOR, B., LEISTAD, Ø., LING, E., PERRY, M., PIACENTE, E., ROSILLO-CALLE, F., RYCKMANS, Y., SCHOUWENBERG, P.-P., SOLBERG, B., TRØMBORG, E., WALTER, A. D. S. & WIT, M. D. 2008. Developments in international bioenergy trade. *Biomass and Bioenergy,* 32**,** 717-729.

KANZIAN, C. & HOLZLEITNER, F. 2006. A new approach in the fuel wood supply chain using a self-loading truck for hauling. Sofia: Forest Research Institute.

KILPONEN, M. 2010. 10 years with slash bundles. More efficiency and flexibility to forest energy logistics. *In:* FINBIO (ed.) *Forest Bioenergy 2010 from 31st August- 4th September 2010. Book of Proceedings, Vol. 47, pp. 129-134.*

KLENNER, W., ARSENAULT, A., BROCKERHOFF, E. G. & VYSE, A. 2009. Biodiversity in forest ecosystems and landscapes: A conference to discuss future directions in biodiversity management for sustainable forestry. *Forest Ecology and Management,* 258**,** S1-S4.

KNIGHT, C. G. 2001. Human-Environment Relationship: Comparative Case Studies. *In:* NEIL, J. S. & PAUL, B. B. (eds.) *International Encyclopedia of the Social & Behavioral Sciences.* Oxford: Pergamon.

KOFMAN, P. D. 2010. *Units, conversion factors and formulae for wood for energy,* Dublin, Ireland, Harvesting / Transportation n.21. COFORD.

KÄRHÄ, K. & VARTIAMÄKI, T. 2006. Productivity and costs of slash bundling in Nordic conditions. *Biomass and Bioenergy,* 30**,** 1043-1052.

LEVENDE SKOG 2006. *Living forest: Standard for sustainable forest management in Norway,* Oslo, Norway, Levende Skog pp.1-40.

LINDHOLM, E.-L., BERG, S. & HANSSON, P. A. 2010. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *European Journal of Forest Research,* 129**,** 1223-1235.

LINDNER, M., SUOMINEN, T., PALOSUO, T., GARCIA-GONZALO, J., VERWEIJ, P., ZUDIN, S. & PÄIVINEN, R. 2010. ToSIA--A tool for sustainability impact assessment of forest-wood-chains. *Ecological Modelling,* 221**,** 2197-2205.

LINDNER, M., WERHAHN-MEES, W., SUOMINEN, T., VÖTTER, D., ZUDIN, S., PEKKANEN, M., PÄIVINEN, R., ROUBALOVA, M., KNEBLIK, P., BRÜCHERT, F., VALINGER, E., GUINARD, L. & PIZZIRANI, S. 2011. Conducting sustainability impact assessments of forestry-wood chains: examples of ToSIA applications. *European Journal of Forest Research***,** 1-14.

MÖLLER, B. & NIELSEN, P. S. 2007. Analysing transport costs of Danish forest wood chip resources by means of continuous cost surfaces. *Biomass and Bioenergy,* 31**,** 291-298.

NOTARO, S., PALETTO, A. 2005. Valutazione economica della funzione produttiva dei boschi in Trentino. *Dendronatura,* 1**,** 8-19.

OZKAN, B., KURKLU, A. & AKCAOZ, H. 2004. An input-output energy analysis in greenhouse vegetable production: a case study for Antalya region of Turkey. *Biomass and Bioenergy,* 26**,** 89-95.

PANICHELLI, L. & GNANSOUNOU, E. 2008. GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass and Bioenergy,* 32**,** 289-300.

PIUSSI, P. 2000. Expansion of European mountain forests. *In:* PRICE, M. F., BUTT, N. (ed.) *Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000.* Wallingford, pp.19-25: CABI International.

PRICE, M. F. 2003. Why mountain forests are important. *The Forestry Chronicle,* 79**,** 219-222.

ROOTZÉN, J. M., BERNDES, G., RAVINDRANATH, N. H., SOMASHEKAR, H. I., MURTHY, I. K., SUDHA, P. & OSTWALD, M. 2010. Carbon sequestration versus bioenergy: A case study from South India exploring the relative land-use efficiency of two options for climate change mitigation. *Biomass and Bioenergy,* 34**,** 116-123.

SCHWAIGER, H. & ZIMMER, B. 2001. A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. *In:* KARJALAINEN, T., ZIMMER, B., BERG, S., WELLING, J., SCHWAIGER, H., FINÉR, L., CORTIJO, P. (ed.) *Energy, carbon and othermaterial flows in the life cycle assessment of forestry and forest products — achievements of the working group 1 of the COST action E9.* Joensuu, Finland: European Forest Institute (EFI).

SEVIGNE, E., GASOL, C. M., BRUN, F., ROVIRA, L., PAGÉS, J. M., CAMPS, F., RIERADEVALL, J. & GABARRELL, X. 2011. Water and energy consumption of Populus spp. bioenergy systems: A case study in Southern Europe. *Renewable and Sustainable Energy Reviews,* 15**,** 1133-1140.

SPINELLI, R. & MAGAGNOTTI, N. 2009. Logging residue bundling at the roadside in mountain operations. *Scandinavian Journal of Forest Research,* 24**,** 173 - 181.

SPINELLI, R., MAGAGNOTTI, N. & DELLAGIACOMA, F. 2008. Meccanizzazione nelle fustaie alpine. Due diversi sistemi di lavoro *Sherwood* 147**,** 45-49.

SPINELLI, R., MAGAGNOTTI, N. & NATI, C. 2010. Benchmarking the impact of traditional small-scale logging systems used in Mediterranean forestry. *Forest Ecology and Management,* 260**,** 1997-2001.

SPINELLI, R., NATI, C. & MAGAGNOTTI, N. 2007. Recovering logging residue: experiences from the Italian Eastern Alps. *Croatian Journal of Forest Engineering,* 28**,** 1-9.

SSB 2011a. Energy. Statistics Norway. *http://www.ssb.no/english/subjects/01/03/10/energi_en/ Visited on September 2011.*

SSB 2011b. Forestry. *Statistics Norway,* http://www.ssb.no/skog_en/.

TAHVANAINEN, T. & ANTTILA, P. 2011. Supply chain cost analysis of long-distance transportation of energy wood in Finland. *Biomass and Bioenergy,* 35**,** 3360-3375.

TRØMBORG, E., BOLKESJØ, T. F. & SOLBERG, B. 2007. Impacts of policy means for increased use of forest-based bioenergy in Norway--A spatial partial equilibrium analysis. *Energy Policy,* 35**,** 5980-5990.

TRØMBORG, E., BOLKESJØ, T. F. & SOLBERG, B. 2008. Biomass market and trade in Norway: Status and future prospects. *Biomass and Bioenergy,* 32**,** 660-671.

VALENTE, C., HILLRING, B. G. & SOLBERG, B. 2011a. Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. *Scandinavian Journal of Forest Research,* 26**,** 429-436.

VALENTE, C., HILLRING, B. G. & SOLBERG, B. 2011b. Greenhouse Gas Emissions, Energy Use and Costs of Wood Fuel Supply Chains in Scandinavia. *Submitted to Journal of Forest Energy*.

VALENTE, C., SPINELLI, R. & HILLRING, B. G. 2011c. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). *Journal of Cleaner Production,* 19**,** 1931-1938.

VAN BELLE, J.-F. 2006. A model to estimate fossil CO2 emissions during the harvesting of forest residues for energy with an application on the case of chipping. *Biomass and Bioenergy,* 30**,** 1067-1075.

VAN DAM, J., FAAIJ, A. P. C., HILBERT, J., PETRUZZI, H. & TURKENBURG, W. C. 2009. Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B. Environmental and socio-economic impacts on a regional level. *Renewable and Sustainable Energy Reviews,* 13**,** 1679-1709.

VENNESLAND, B., HOBBELSTAD, K., BOLKESJØ, T., BAARDSEN, S., LILENG, J., ROLSTAD, J. 2006. *Skogressursene i Norge 2006. Muligheter og aktuelle strategier for økt avvirkning,* Ås, Norway, Skog og landskap - 03/2006.

WIHERSAARI, M. 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass and Bioenergy* 28**,** 435–443.

ZIMBALATTI, G. & PROTO, A. R. 2009. Cable logging opportunities for firewood in Calabrian forests. *Biosystems Engineering,* 102**,** 63-68.

ISBN 978-82-575-1020-6
ISSN 1503-1667

Hedmark University College
Campus Evenstad

Hedmark University College
Faculty of Applied Ecology and Agricultural Sciences
Campus Evenstad, NO–2480 Koppang, Norway
www.hihm.no/English/Campus-Evenstad

Norwegian University of Life Sciences
NO–1432 Ås, Norway
Phone +47 64 96 50 00
www.umb.no, e-mail: postmottak@umb.no