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

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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 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 mountaindwelling 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 CO2 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 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 m3 s.o.b.) delivered to the terminal. The use of raw materials (m° 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 (GWP100) for the emissions of carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O).

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.

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

The results of GWP100 (g CO_2e/m^3s.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 GWP100 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^3s.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 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/m³ 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.

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Figures

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

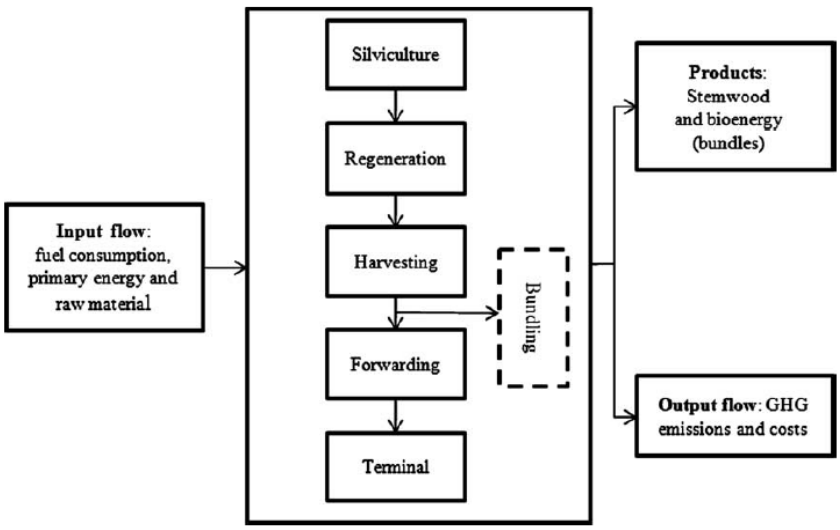

Figure 2. System boundary of the mountain forest fuel system: main unit processes and flows involved in the life cycle assessment. Dotted line: expansion of the system boundary.

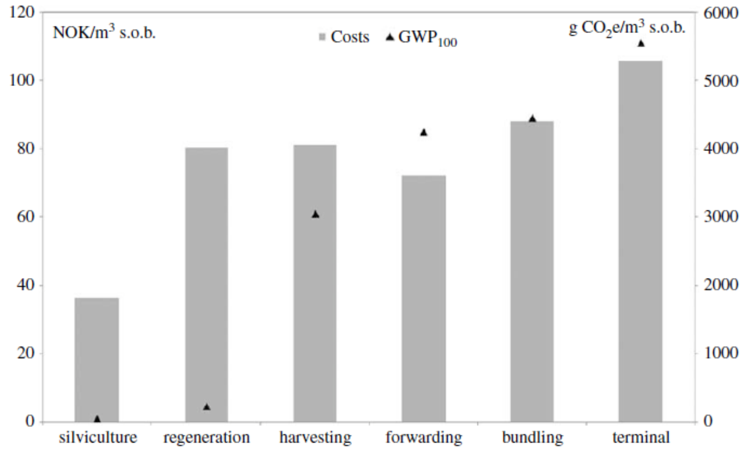

Figure 3. Characterization results for climate change GWP_{100} (g CO_2e/m^3 s.o.b.) and costs (NOK/m^3 s.o.b.). Total emissions 17,600 g CO_2e/m^3 s.o.b., and total costs 463 NOK/m^3 s.o.b. Note: 8 NOK = 1 euro.

Tables

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)

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

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