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

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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 alternative wood fuel supply chains (WFSCs) with respect to greenhouse gas (GHG) emissions, energy use, and costs. Case study 1 is a local Norwegian supply chain, while case studies 2 and 3 are international WFSCs, where woody biomass is exported to Sweden from respectively lowland and mountain forests in Norway. The GHG emissions and energy use in the case of wood chip exportation from Norway to Sweden were lower than in the local alternative use of the biomass. The emissions were 31.7 kg CO_{2e}/m^3 solid over bark (67.4 kg CO_{2e}/MWh) for case study 1; 22.2 kg CO_{2e}/m^3 solid over bark (47.2 kg CO_{2e}/MWh) for case study 2; and 23.9 kg CO_{2e}/m^3 solid over bark (50.8 kg CO_{2e}/MWh) for case study 3. 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 GHG emissions occurred in the truck transportation and chipping operations. Energy input-output ratios show that for case studies 1, 2, and 3, respectively, the fossil fuel energy inputs were 4.5%, 3.4%, and 4% of the bioenergy produced. Forest fuels from mountain forests in Norway seem promising 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 plants substituted energy production from coal and oil plants. The cost analysis showed that wood chip import from Norway to Sweden was economically feasible.

Keywords: bioenergy, LCA, mountain forests, Norway, supply chains, Sweden.
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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 for a sustainable future. The use of woody biomass for energy production could contribute not only to greenhouse gas (GHG) reduction, but also to creation of secure and diversified energy markets and generation of 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 50 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 (50%). Only 1% of the total energy production is generated in district heating (Statistics Norway 2011). Bioenergy production in Norway has been limited because of little investment and few incentives (IEA 2009). On the contrary, bioenergy production in Sweden has had a very high share of about 29% (Swedish Energy Agency 2008). Sweden has doubled its proportion of bioenergy pro-

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duction over the past 30 years, thanks in part to heavy subsidies and tax incentives. In only one year, bioenergy consumption increased by 12 TWh in Sweden, while Norway could need the next 10 years to attain that increase (Svebio 2011). 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 wood fuel supply chains (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 a 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 above-mentioned factors. Specific objectives are to (i) perform a life cycle assessment (LCA) of these three WFSCs from the forest stand to the bioenergy plant, (ii) calculate the GHG balance of replacing fossil fuels and electricity by forest fuels at the bioenergy plants, (iii) analyse the costs of the various parts of the biomass procurement, and (iv) identify the WFSC that has fewer emissions and less energy use.

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 manner of transport have been performed by Lindholm and Berg (2005). Environmental load and energy use of long-distance transport 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 the Swedish wood chip supply chain and compared Swedish and Finnish bundle systems. Kärhä (2011) studied the industrial supply chain based on wood chips in Finland. Hakkila (2004) evaluated several alternatives for forest fuel production systems based on wood chips in Finland.

Examples of studies from other European countries come from Van Belle (2003), analysing a forest fuel supply chain for providing forest residues to power plants in Belgium, and Damen and Faaij (2006), performing a greenhouse gas balance of the 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. (2011), respectively, in Austria and in Italy. Cherubini et al. (2009) performed an overview of the bioenergy chain, including the forestry residues chain, performing energy and GHG balances in comparison to a 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.

Materials and Methods

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 analysed system. We used LCA to compare alternative systems based on the case studies. Case study has 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 study is a good way for testing hypotheses and helping to develop scientific innovation, thereby increasing knowledge (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 (m^3 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_2 equivalent (CO_{2e}) per m^3 s.o.b. and kWh/m^3 s.o.b., respectively.

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. Analyses of the cost of raw materials delivered to the terminal, chipping operation, and wood chips delivered to the bioenergy plants were performed using standard economic methods based on prevalent market prices for each country.

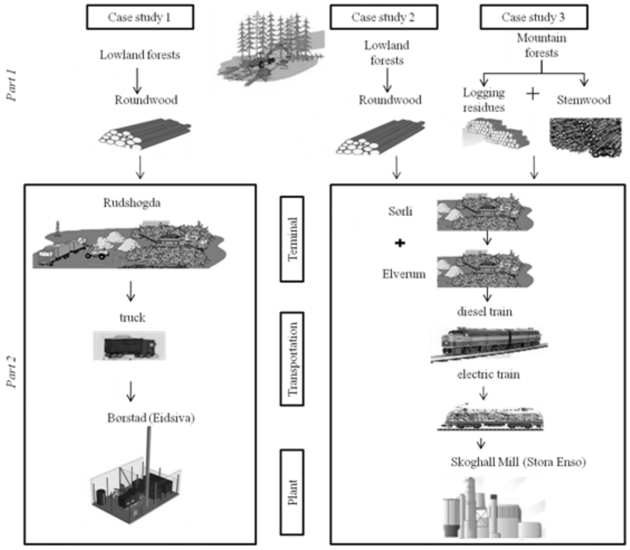

Figure 1. *System boundary of the wood fuel supply chains (WFSCs): case study 1 (local WFSC) and case studies 2 and 3 (international WFSC). Part 1: from the forest stand to the terminal. Part 2: from the terminal to the plant.*

System Boundary and Case Studies

The system boundary, illustrated in Figure 1, includes the entire wood fuel supply chain (WFSC), consisting of two main parts of the production chain—the first from the forest stand to the terminal, and the second from the terminal to the combustion plant.

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, as shown in Valente et al. (2011a) derived from logging residues (i.e., tree tops and branches) and from stemwood, while wood chips from lowland forests are derived from conventional roundwood.

In case study 1, the raw materials, mainly roundwood 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 (Table 1). 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 Energy, was the main consumer of wood chips, taking about 38500 m^3 loose volume (32766 MWh).

The raw materials were assumed to come from forests located in lowland forests (case study 2) and mountain areas (case study 3). 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. 2011a). All raw materials in the form of roundwood coming from lowland forests were assumed 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, a Swedish manufacturer of carton-board for packaging and printing purposes owned by Stora Enso (Figure 2), and 25%, about 40000 m^3 loose volume (34042 MWh), were used locally.

An additional 33000 m^3 loose volume (28085 MWh) of wood chips from mountain forests in the form of logging residues and stemwood (case study 3) were assumed collected at the terminal of Elverum. The first part of case study 3 was based on results from Valente et al. (2011a), while the second part was in common with case study 2. The logging residues were assumed arrived at the terminal in bundles (Valente et al. 2011a) to fill up the train from Sørli terminal to Skoghall Mill. This factory buys electricity and fuels from external suppliers while also producing electricity and heating steam itself. Seventy percent of this internal production is based on bioenergy. The energy production based on Norwegian biofuels represented a marginal quantity of the Skoghall Mill production.

All wood chips were dried over the summer to attain better fuel quality.

Each terminal had access to one chipper and owned a front loader mounted on an excavator for loading chips and making piles.

The transportation routes (Figure 2) covered distances of 22 km by truck between Rudshøgda terminal and the Børstad plant at Hamar in case study 1 (local WFSC), and 285 km between Sørli and Skoghall Mill (i.e., 134 km by diesel train, and 151 km by electric train) passing by Elverum (international WFSC—case studies 2 and 3). Diesel trains were used instead of the electrified line to avoid the transit in the Oslo area.

Table 1. *Amounts of wood chips assumed to annually be handled in the case studies.*

Case study	Facilitity	Type	Amount of chips/year	
			m^3 loose	MWh
1	Rudshøgda	Terminal	75000	63830
	Børstad	Plant	38500	32766
2 & 3	Sørli	Terminal	130000	110638
	Elverum	Terminal	33000	28085
	Skoghall Mill	Plant	123000	104681

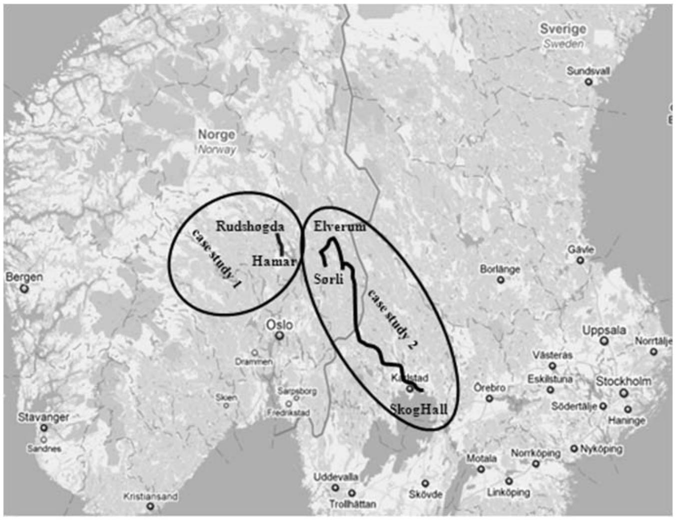

Figure 2. *Map of case studies 1, 2 and 3.*

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 (Tables 1 and 2) for each case study. Fuel consumption was compared against other literature studies (González-García et al. 2009, Hansson et al. 2003, Michelsen et al. 2008, NSB 2010 & 2011, Van Belle 2006). The fuel consumption of chipping and loading operations was identical in all case studies because of the use of the same types of machinery. Productivity of chipping was assumed to be similar in all three case studies, although it should be usually higher for roundwood than for logging residues. The conversion factor for transforming m^3 loose into m^3 s.o.b. was 0.4, while it was 2.12 for transforming m^3 s.o.b. into MWh (ÖNORM 1998). Consequently, in relation to different moisture content of the wood fuel, the MWh/m^3 s.o.b. are between 1.76 and 2.10 respectively for logging residues with 60% moisture content, and for roundwood with 20% moisture content, when the energy content is 19.5 MJ/kg dry matter. Storage time of wood chips was less than 1 year. The energy content of diesel was 10.1 kWh. The environmental load of the first part of the supply chain—from the forest to the terminal—was estimated using GHG data from a Norwegian case study by Michelsen et al. (2008) for lowland forests and Valente et al. (2011a) for mountain forests. It included silviculture, planting, harvesting, forwarding, and transportation to the terminal. Bundling of forest residues was integrated in the first part of the mountain WFSC. The average transport distance of roundwood from lowland forests was 43 km (Per Magne Bryhn, Mjøsen Skog BA, pers. comm. 2011) and 64 km from mountain areas (Valente et al. 2011a). For the homogeneity with Valente et al. (2011a), planning 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.

An energy input-output ratio was performed according to previous study (Valente et al., 2011b) 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 (2.12 MWh/m^3 s.o.b.). A sensitivity analysis was performed for chipping, loading, and transport by truck and train, assuming respectively 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 wood fuel from local lowland forest substituted for a heating plant based on natural gas, coal, or electricity in Børstad, and wood fuel from lowland and mountain forests substituted for 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) based on Harju (2001) for Skoghall Mill. Efficiency, installed capacity, and emissions of both plants based on wood and fossil fuel (Table 3 and 4) were based on the assumption of carbon neutrality—i.e., based on the concept that fossil fuels are net contributors of CO_2 emissions, contrary to energy from wood where CO_2 circulates in a biological system, maintaining stable levels in the atmosphere. Continuous carbon circulation between forests and the atmosphere is assured by forest growth, differently from the fossil fuel system. 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. Internal reports were consulted in Børstad (KMP 2010, Larsson 2010)

Table 2. *Fuel consumption and loading capacity for processes and machinery in the case studies.*

Case study	Process/machinery	Fuel consumption		Loading capacity		Containers/ trip	Trips/ year
		l/m^3 s.o.b.	l/MWh	m^3 loose	MWh		
1,2 & 3	Chipping [a)]	1.2	2.5	-	-	-	-
1,2 & 3	Loading [a)]	0.2	0.4	-	-	-	-
1	Container truck b)	2.16	4.6	90-100	76-85	3	330
2 & 3	Train [c)]	0.33 [d)]	0.7 [d)]	1537	3270	70	32

Data obtained from [a)] Per Magne Bryhn, Mjøsen Skog BA (pers. comm. 2011), [b)] Hohle (2008) and [c)] Lennart von der Burg, Hector Rail AB (pers. comm. 2011) and Leif Löfgren, Stora Enso Skoghalls Bruk (pers. comm. 2011). [d)] Fuel consumption assumed for diesel train. Electric train was assumed to consume 1.96 kWh/m^3 s.o.b.

Table 3. *Installed capacity, efficiency and emissions from wood chips combustion of Børstad and Skoghall Mill plant.*

Parameter	Unit	Plant	
		Børstad	Skoghall Mill
Installed capacity	MW	5	135
Efficiency	%	85	87
Emission from wood chips combustion	kg CO_{2e}/ m^3s.o.b.	5	1
	kg CO_{2e}/ MWh	10	2

and in Skoghall Mill CHP plant (STORAENSO 2010a, STORAENSO 2010b, STORAENSO 2010c, STORAENSO 2011) for making an inventory of non-GHG emissions from both bio-boilers. Data related to costs of wood chips at the terminal and chipping operation were obtained from interviews (Per Magne Bryhn, Mjøsen Skog BA, pers. comm. 2011). Costs of chipping operations of wood fuels from mountain forests were not available. Data related to the costs of wood chips at the plants were assumed to be 10% lower than the prices of wood chips delivered at the DHP of Børstad and the CHP plant of Skoghall Mill as reported in the energy reports from Norway (Tekniske Nyheter DA 2011) and Sweden (SCB 2010). The actual production costs of heat and electricity based on wood fuels at the bioenergy plants were not obtainable because it was classified by the industries as secret information.

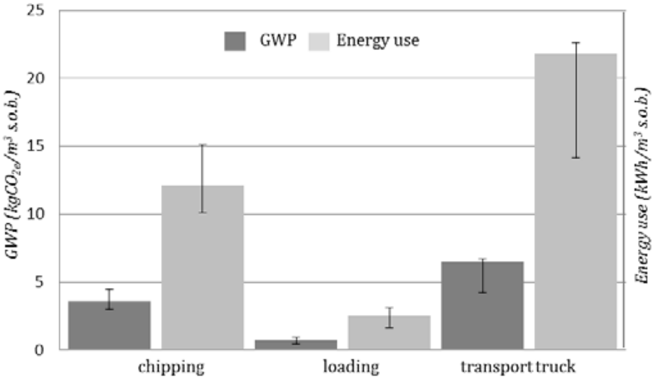

Figure 3. *Case study 1: Global warming potential (GWP) ($kgCO_{2e}/m^3$ s.o.b.) and energy use (kWh/m^3 s.o.b.) from the terminal to district heating plant. Vertical bars indicate the range of the results when applying fuel consumption values from various studies performed in Nordic countries (Hansson 2003, Hohle 2008, Michelsen et al. 2008, and González-García et al. 2009).*

Table 4. *Levels of emissions from different plant and fuel types that were assumed to be substituted by use of wood fuels*

Case study	Plant type	Fuel type	Substituted Emissions	
			kg CO_{2e}/ MWh	kg CO_{2e}/ m^3 s.o.b. [a]
1	Heating plant	Natural gas	221	104
		Oil	451	212
		Electricity	81	38
2 & 3	Cogeneration plant	Natural gas	380	179
		Oil	368	187
		Coal	783	368

[a] *Assuming that fuel wood is carbon neutral and that 2.12 m^3 s.o.b. is required to produce one MWh, this value indicates the emissions substituted per m^3 s.o.b. of wood fuel used.*

Results

GHG Emissions

In case study 1 (Figure 3), the GWP from the terminal to the DHP is 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.).

Instead, in case studies 2 and 3, the GWP of the second part of the WFSC—from the terminal to the CHP plant—was 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. (Figure 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

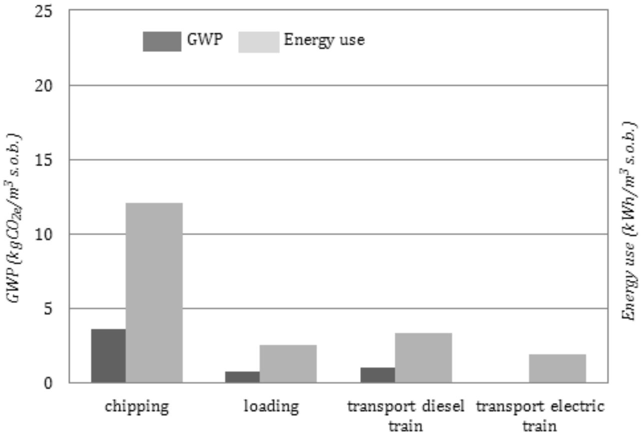

Figure 4. *Case studies 2 and 3: Global warming potential ($kgCO_{2e}/m^3$ s.o.b.) and energy use (kWh/m^3 s.o.b.) of the second part of the wood fuel supply chain (WFSC)—from the terminal to the CHP plant.*

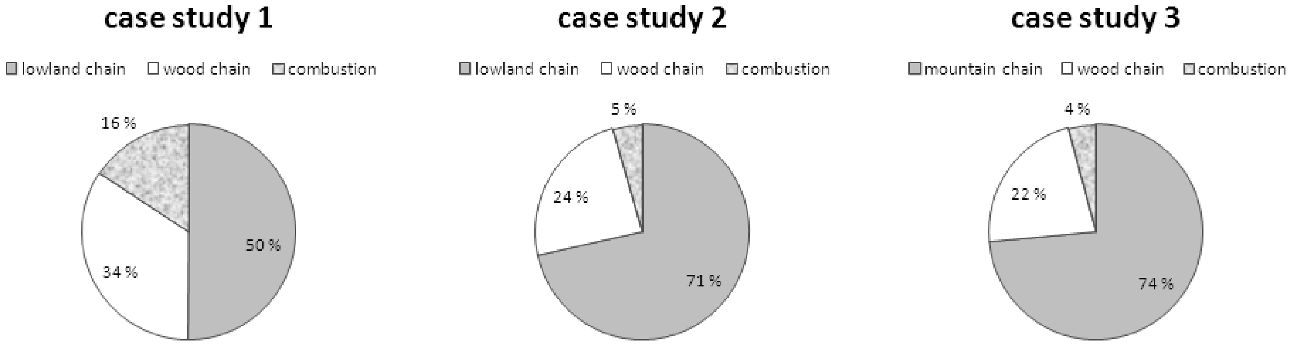

Figure 5. *Overall global worming potential (GWP) in percentage for case studies 1, 2 and 3.*

the chipping operation, while the lowest was from transportation by electric train.

The first part of the WFSC—from the forest stand to the terminal—had a total GWP of 15.9 kg CO_{2e}/m^3 s.o.b. (33.8 kg CO_{2e}/MWh), when considering only the raw materials from lowland forests (case study 2), while it was 17.6 kg CO_{2e}/m^3 s.o.b. (37.4 kg CO_{2e}/MWh) when it included raw material from mountain forests as well (case study 3).

The GWPs of the wood fuel supply chain were 31.7 kg CO_{2e}/m^3 s.o.b. (67.4 kg CO_{2e}/MWh) for case study 1, and 22.2 kg CO_{2e}/m^3 s.o.b. (47.2 kg CO_{2e}/MWh) and 23.9 kg CO_{2e}/m^3 s.o.b. (50.8 kg CO_{2e}/MWh) for case studies 2 and 3, respectively.

In the WFSC (Figure 5) of case study 2, the first part of the supply chain in case study 3 used 3% more GWP than case study 2. Compared to case study 1, the second part of case studies 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.

The energy input-output ratio showed that for case studies 1, 2, and 3, respectively, a fossil fuel energy input of 4.5%, 3.4%, and 4% was necessary for producing energy output based on wood fuels.

Figures 6 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. 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.

The sensitivity analysis of the WFPC (Figure 7) showed that the change in the input parameter fuel consumption influenced the energy use of transport based on diesel truck and chipping operations.

Table 5. *Emission levels from the Børstad and Skoghall Mill bio-boilers according to measurements by accredited test laboratories.*

Parameters	Unit	Børstad	Skoghall Mill
NO_x	kg/MWh	0.21	0.18
SO_x	kg/MWh	n.a.[c]	0.05
CO	mg/Nm^3 (6% 0_2) [b]	42	100
Dust	mg/Nm^3 [b]	< 5	7.3
TOC [a] (mainly CH_4 and CH_3)	mg/Nm^3 [b]	n.a.	< 2-3
NH_3	mg/MJ	n.a.	6.34
Ash content	% of dry matter	1.6	n.a.

[a] *TOC = total organic component.*
[b] *Nm^3= normal cubic meter, a standard reference conditions of temperature and pressure used to define gas volume.*
[c] *n.a. = not applicable.*

Table 6. *Costs for the processing and delivery of wood chips according to the average market prices in 2011.*

Case study	Cost component	Cost	
		€/ m^3 s.o.b.	€/ MWh
1,2 & 3	Raw materials at the terminal [a)]	0.75	1.6
1,2 & 3	Chipping operation [b)]	6	12.8
1	Wood chips at Børstad		
	At moisture content <35%	13	27.6
	At moisture content >35%	11	23.4
	In average	12	25.5
2 & 3	Wood chips at Skoghall Mill	8	17

[a)] *source: Per Magne Bryhn, Mjøsen Skog BA, pers. comm. 2011*
[b)] *chipping cost for wood chips from mountain forests was not available*

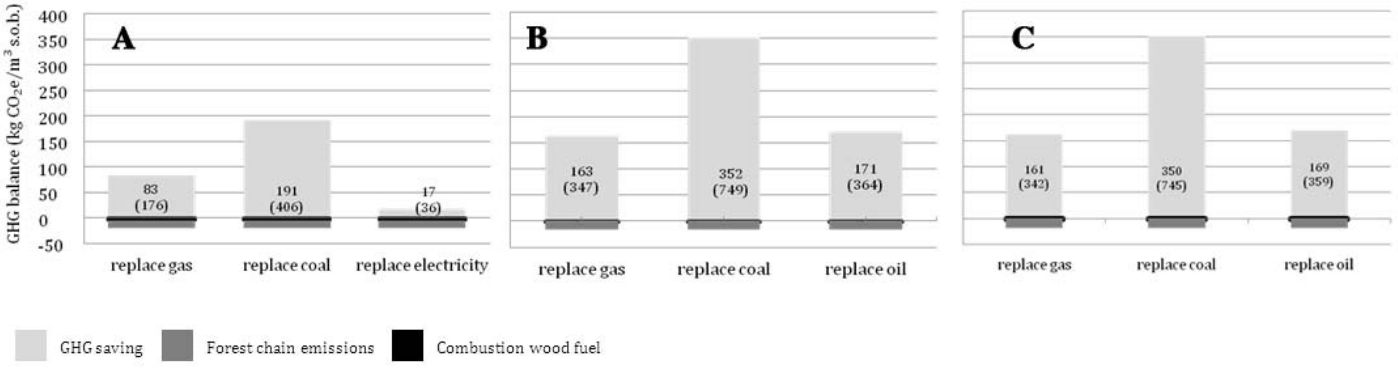

Figure 6. *Greenhouse gas (GHG) balance of case study 1 (pane A), 2 (pane B) and 3 (pane C) in kg CO_{2e}/m^3 s.o.b. and kg CO_{2e}/MWh in brackets. Pane A included only the forest chain emissions, pane B the lowland forest chain emissions and pane C the mountain forest chain emissions. In each pane, the three bars show the GHG balance when wood fuels substitute fossil fuel and electricity. Emissions compensated (GHG saving) and not compensated (combustion of wood fuel and forest chain emissions) by the substitution are, respectively, in the positive and negative part of the chart. In pane A, B and C emissions not compensated by substitution are, respectively, 21, 17 and 18 kg CO_{2e}/m^3 s.o.b. (44 kg, 36 kg and 38 kg CO_{2e}/MWh).*

Non-GHG Emissions

The bio-boiler in Skoghall Mill (case studies 2 and 3) had lower measured NO_X emissions, but higher CO emissions (more than double) and dust (2 mg/m^3 more) than the bio-boiler in Børstad (case study 1) (Table 5).

Cost Analysis

Results of the cost analyses are shown in Table 6. Low moisture content (< 35%) corresponded to better quality of wood chips, but higher costs. However, it is often considered an advantage to transport dry wood chips, because of their higher energy density (Andersson et al. 2002). Cost of chipping operations for logging residues from mountain forests were not available, but it could be assumed higher than for roundwood from lowland forests. At the Børstad plant (case study 1) the cost increase was 2 €/m^3 s.o.b. (4.2 €/MWh). The difference in cost between the wood chips bought at the Skoghall plant (case studies 2 and 3) and the average cost at Børstad was 4 €/m^3 s.o.b. (8.5 €/MWh).

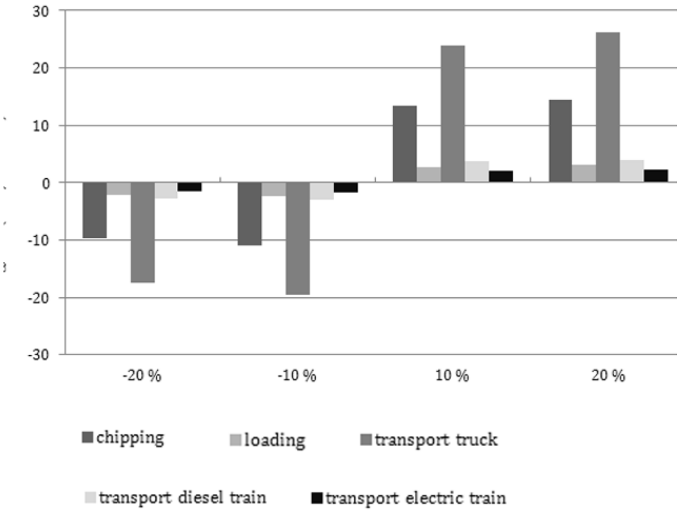

Figure 7. *Sensitivity analysis of the wood fuel supply chains: decrease and increase of 10% and 20% of the parameter fuel consumption and effect on the energy use compared to the base scenario.*

Discussion

Case study 1—i.e., the local WFSC—had the highest GWP and energy use within all three case studies, mainly due to the road transportation system and higher emissions at the combustion plant. The WFSC of case studies 2 and 3 differed little in the GWP and energy use (Figure 4), even though the first part of the mountain WFSC (case 3) produced greater emissions and had higher energy use than the lowland first part (case study 2). The energy input-output ratio indicated that case study 1 requires 1.2% more energy input than case study 2. Little difference in energy use between case study 1 and 3 indicates that the introduction of the first part of the mountain supply chain into the WFSC may not greatly increase both GHG emissions and energy demand. A low level of energy input compared to energy output (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 WFSCs and at the conversion plants, was positive, especially when the considered wood chip plants replaced coal and oil plants. A large amount of GHG emissions can be eliminated by the replacement of fossil fuel with biofuel (Wihersaari 2005).

The GHG balance was better at Skoghall Mill (case studies 2 and 3), when compared with the Børstad plant (case study 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 a smaller system like 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 boiler renovation using black liquer 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 world's most modern paperboard mills, where cogenerated energy was both consumed and produced. The use of wood fuels makes it possible 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 in the form of heat can be delivered to the district heating network, constituting further income for this mill. On the contrary, 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, the chipping operation had the highest GWP and energy use, and it was one of the processes most sensitive to changes in fuel consumption. The substitution of a diesel-powered chipper with an 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 intensifying 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, regarding both the environment and forest laws.

The present study suggests that the combination of harvesting forest residues, chipping at the terminal, transportation distance based on railroad, and a 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 for storage wood fuel, especially from mountain areas, and a safe supply make it preferable to use 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 amounts 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. This fact confirms that low-quality wood from mountain forests can be exported from Norway to Sweden. Forest fuels from Norwegian 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 the transport distance will become longer, and alternative transport, such as electric trains, will 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 trains requires a smaller amount of energy, and it is a more efficient and clean system.

Study from Tahvanainen and Anttila (2011) related to supply costs identifies supply based on train transport as the most cost-effective even when the transport distance is shorter than 100 km. These elements support the idea of introducing railroad transport in the terminal of Rudshøgda (case study 1). However, at the moment, the Norwegian railway network is underdeveloped 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 a dry or cold year, Norway is a net importer of electricity based on a non-renewable energy source, producers of GHG.

The GHG emissions from transportation can be further reduced by using the loading capacity of transport systems in a better way, choosing the roads optimally, and improving transport technologies (Hamelinck et al. 2005).

An 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 is to increase the loading capacity of Norwegian trucks or replace trucks powered by fossil fuels with those 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 a 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 6, is related to the moisture content. Skoghall Mill can buy at a low price and treat low-quality wood chips with high moisture content, such as those from Norwegian mountain forests.

It is important to highlight that Sweden can continue to import raw material from Norway until the market prices are economically convenient. In the opposite case, Skoghall Mill can consider importing raw material from other countries, using the connection to the sea through the lake Vänern.

Conclusions

Our study highlights how differences in handling wood fuel, transport system, and conversion plants affect the amount of GHG emissions and energy use. In the present article, we analyse the WFSC with lower GWP and energy use in dealing with the exportation of wood fuel from Norway to the neighbour country Sweden. Changes in fuel consumption critically affect the energy use of chipping operations and transportation by truck. Railway transport, even based on diesel trains, has less air pollution than road transportation. The energy input-output ratio indicates that all case studies need a low amount of energy for producing bioenergy. According to our case studies, the harvest of Norwegian forest fuel having mountain origins and respecting environmental regulations can be an additional source of wood fuel exports to a country having the high bioenergy production efficiency of Sweden. In this case, the GHG impact from longer transport distance is compensated by the use of a less-polluting transport system like electric trains and better efficiency at the conversion plant. Our results show that substitution of fossil fuel, especially coal and oil, by wood fuel has positive benefits in the mitigation of climate change. Cost analyses show it is economically advantageous to export wood chips from Norway to Sweden, at prevailing market prices. The GHG balance indicates that large CHP plants save more emissions per functional unit compared to smaller plants, due to the high efficiency in the conversion process. In conclusion, our study indicates it is feasible today to export wood chips from Norway to Sweden with reduced GHG emissions and costs, relative to utilizing the wood in Norway.

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