Costs, CO_2-emissions and energy balance for applying Nordic methods of forest biomass utilization in British Columbia

Kostnader, CO_2-utsläpp och energibalans för tillämpning av Nordiska metoder att tillvarata skoglig biomassa i British Columbia

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Abstract

A devastating mountain pine beetle (MPB) infestation in British Columbia has had enormous economic consequences for the lumber industry and has been one of the drivers for the development of bioenergy systems. Transportation is the link between forests and the end-users and also a critical factor for profitability. Transport efficiency can in the bioenergy context be evaluated by the costs, but also by the discharged CO_2-emission levels and its energy balance.

The objective of this study was to evaluate three transportation systems with the central difference in the processing level of slash. The feasibility of MPB-killed biomass was compared with vigorous biomass and all systems were modeled over a range of transport distances. Results are expressed in Canadian $/MWh, kg CO_2/MWh and ratio between consumed and harvested energy (%).

The Hog fuel-system, with a grinder allocated to the roadside, was generally the most economical alternative irrespective of slash amount at landing or transport distance. To produce bundles at roadside and transport to the end-user was the most economical alternative for small amount of slash (corresponding to 10 ha final felling) at landing and transport distances over 250 km. Under such conditions the combination of fairly good truckload capacity and low allocation costs compensated for the low bundler productivity. It was in all assessed comparisons least economical to transport the slash in its uncomminuted form to grind it into hog fuel after deliverance to industry. The Bundle-system and the Hog fuel-system had the lowest respectively the highest levels of discharged CO_2-emissions. The systems' energy consumption corresponded to 3-10% of the harvested energy, with the Bundle-system and the Hog-fuel system being the most and least, respectively, energy efficient system.

Both the Hog fuel-system and the Bundle-system are viable opportunities for the recovery of B.C.'s available biomass resources. MPB-killed biomass increased the transport efficiency as it resulted in lower costs and lower levels of discharged CO_2-emissions.

Keywords: transportation, biomass supply, bioenergy, slash, logging residues, grinder, bundle

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Björn Nilsson

1 Introduction

1.1 Background

Sweden's long history of forestry activities and their role as somewhat pioneers within bioenergy issues, has raised the needs and goals of a more complete utilization from the harvest of forests. Hence, what in Europe commonly is called logging residues and in North America slash, i.e. treetops and branches, has become an important assortment for energy production and a substitute for fossil fuels in both industrial and thermal plants. In this study the term slash was used. In Sweden, district heating and the development of today's thermal power stations has been favored and formed by different kinds of policies and subsidies. A reform of the governmentally operated electricity market in 1996 let new producers in and opened for competition and reductions of the electricity price and cost levels. After the reform thermal stations for district heating began to utilize their power generating capacity more than for their own needs and to sell electricity on the national public power grid (Andersson, 2008). The introduction of the "electric certificates" (Sw. Elcertifikatsystemet) the 1st of May in 2003 aimed for an increased rate of the renewable power production by a raised profitability. By January in 2005 all forms of combustible and organic waste materials were restricted for deposits, which established a market on wastes and garbage. Since January in 2006 private households can apply for subsidies to convert their oil furnace or electric water heater for a connection to district heating (Lundborg, 2008).

Along with the district heating expansions, and of course buildings' insulation improvements, Sweden has seen a 70 percent reduction in their oil consumption in the latest 30 years (Andersson, 2008). Biomass as feedstock for district heating is of a substantial value in manner of reaching the oil-independency by 2020 as stated by the Swedish Government and the former Prime Minister Göran Persson's Oil-commission (Energimyndigheten, 2007).

About the same time as sawmills grew big in Sweden, the first railroad was entering British Columbia's (B.C.) deep forests. The forestry activities took a quick pace as lots of small forest industry-based communities where established over the province (Macek, 2006). In this humid and mountainous landscape, many communities today have their power supply from B.C. Hydro's dam constructions. Heat has foremost been taken from natural gas, coal and oil, while district heating never really has come into practice, at least not by scale and with wood fueled boilers. B.C. is however a big pellet producer and residual waste wood from sawmills etc. is used as resource. By raised environmental concerns and a national call for clean and renewable energy, B.C. Government in 2002 formed the Energy Plan, with the main focus to decrease the existing oil, coal and gas consumption. The commitment under the Kyoto Protocol is to reduce the national level of greenhouse gas emissions from 1990 to 94 % by 2012 (Williams, 2005). Beyond that, the Ministry of Environment has set a mandatory goal on national level to reduce these emissions of 2006 to 80 % to the year 2020 (Government of Canada, 2007).

By reaffirming the Energy Plan from 2002, a new plan was developed in 2006, in which the B.C. Government stated a Bioenergy Strategy to advance bioenergy research, technology and project development for domestic and international markets. With the mountain pine beetle (MPB) (*Dendroctonus ponderosae*) infestation rising from the beginning of the century and its resulting 10 million hectare of dead forest (circa 960 million m^3 of woody biomass) as a catalyst, numerous projects have aimed for salvation of the infested timber (Kumar et al., 2007).

Biomass that lost its' value as lumber can still be feasible as feedstock for alternative industries. Ralevic and Layzell (2006) estimated the amount of biomass available from existing forestry operations and that potentially can be used for bioenergy in B.C., to approximately 11.9 million raw tonnes per year, which would equal about 53 TWh/yr (assuming the energy content 4.4 GWh/t). Even though the political driving forces and the focus on implementing the Bioenergy Strategy is strong, most research and projects has gone towards using forest residues as an alternative electric power source. The Forest Engineering Research Institute of Canada (FERIC) has drawn numerous studies on cost of harvesting, transporting and comminuting, which later has served as base for further studies. Kumar et al. (2007) did a techno-economic analysis of a projected power plant in Quesnel, where they studied costs of a total system from harvest to combustion. The study aimed fully towards electrical power production and did only cover transportation of the feedstock as wood chips, processed at roadside. The province still lacks studies for the biomass potential by other comminuting techniques and ways of transportation.

The conventional ground based clear fellings of whole-tree harvest results in enormous amounts of slash that are piled, or stacked, and burned at roadside without further utilization. Subsequently there are also great amounts of emissions associated to the burned biomass that are released to the atmosphere every year from B.C.'s forests. With recovery of the slash by transport for combustion in combined heat and power stations (CHP-stations), both electric power and heat can be produced in a green and clean manner.

The B.C. Minister of Energy, Mines and Petroleum Resources recently signed a Joint Statement on bioenergy and biorefining with the Swedish Ministry of Enterprise, Energy and Communications (Sw. Näringsdepartementet) to encourage greater linkages between B.C. and Sweden in focus of bioenergy. This thesis is aligned with the intent of the Joint Statement and with the goals and objectives of the Bioenergy Strategy (B.C. Government, 2008a).

1.2 Roadside piles in Sweden and B.C.

As a result of the forest final fellings, limbs, tops and small trees fall out as slash. By differences in tradition, infrastructure, industries and demand, commercial logging systems differ when comparing B.C.'s and Swedish practices. Roadside piles are found in both regions, although with differences in both shape and orientation, due to their different causes.

In the Nordic countries in general the roadside piles are intended products of the commercial final felling (Andersson et al., 2002). The dominating cut-to-length (CTL) method, with a bioenergy-adapted standard, results in piles of logs and heaps or small piles of slash on the harvested block. The slash can be called the "third assortment" or the "energy assortment", which is forwarded to the roadside in the same manner as the recovery of logs for lumber and pulp. An exception, although quite common, is when the slash are comminuted into wood chips in the terrain and then transported in containers throughout the supply chain. Another exception, although more rare, is when the slash are compressed into bundles (by a special equipped forwarder) already in the terrain and then forwarded to roadside and transported as bundles all the way to the end-user or a terminal.

In B.C. the conventional ground based final fellings is conducted by the "whole-tree" method, i.e. the felled trees are carried out from the block to the roadside. A common combination is a feller-buncher and a grapple skidder. At roadside the trees are laid up in supply piles for a subsequent mechanical processing, often by a dangle head processor. The dangle head processor retrieves the whole trees from the supply pile, delimb and top them and then pile the processed logs close to the road. The branches and tops are discarded to a slash pile, approximately 10-13 meters from the centerline of the road (MacDonald, 2006).

With the relatively low value of the material, the transportation techniques are a critical factor for profitability in bioenergy systems (Ranta and Rinne, 2006) and a possible progress towards bioenergy-adapted harvestings. Moreover, the fuel consumption and the discharged CO_2-emission levels are also crucial when analyzing highly mechanized systems. Therefore it is important to evaluate different possible supply solutions in order to adapt both minimized costs and emissions to the given conditions. Transportation techniques used in Sweden were stipulated as being suitable benchmarks for B.C., but required to be adapted to the conditions in B.C.

1.3 Objectives

Approaching forests as a renewable resource and with potential to mitigate climate change (Verkerk et al., 2008), this study aims to find alternatives to the traditional pile burns at forest roadside in B.C. The objective was to evaluate the potential in three supply systems of both vigorous and MPB-infested biomass. The potential was analyzed as cost efficiency and CO_2 mitigation. The three systems mainly differ in processing level of slash in road transportations. The comparisons were made over available slash amounts at landings and transportation distances.

Given the newly arisen interest for roadside waste recovery in B.C., this study is conducted for end consumers of such industries that can utilize comminuted woody biomass as a resource. Hence, the study's results are relevant for e.g. pellets industries, power plants and thermal stations for district heating.

2 Methods and materials

2.1 Data

The study is mainly based on published literature but complemented with field studies and contacts with both Swedish and Canadian companies and experts. In Sweden different district heating stations were visited and contacted both in the north and south and interviews were held with questions regarding their supply chains, the feedstock, the boiler and the district heating net. In contacts with the forestry companies, which generally were the contractors of both the final felling and the road transport, the interviews covered the entire bioenergy adapted felling procedures. Non-published data from interviewed experts were referred to as e.g. Swedish Experts (2008), unless the expert had agreed on being referred to.

Regional conditions and systems of wood supply for biomass district heating in Sweden was compared with the conditions, legislations and current forestry practices in B.C. Field studies in Canada covered meetings with researchers, machine operators, machine manufactures, forestry companies and contractors of transportation. Literature that was studied covered mostly studies regarding biomass features, natural conditions of B.C. and technical data on machineries used in the province.

2.2 System analysis

2.2.1 Selected systems

Three different transportation techniques for the recovery of slash in Sweden were chosen. The systems were considered likely to be suitable regarding the fact that conventional final felling systems in B.C. result in piles of slash at the roadside. Two of the systems can be described as of the conventional Swedish standards, while the third is more of a visionary character, i.e. is still a prototype. The evaluated systems were:

1) **Slash-system:** Unprocessed slash in pile at roadside – still as loose slash on trucks – comminuted into hog fuel (appendix 3), i.e. grinded fractions, by a grinder at industry
2) **Hog fuel-system:** Unprocessed slash in pile at roadside – comminuted into hog fuel by a grinder at roadside – transported as hog fuel – unloaded at industry
3) **Bundle-system:** Unprocessed slash in pile at roadside – bundled by a truck-mounted bundler at roadside – transported as bundles on trucks – comminuted into hog fuel by a grinder at industry

Figure 1. Schematic figure of the three evaluated systems and their main machinery.

Figur 1. *Schematisk skiss över de tre undersökta systemen och de maskiner som används i dessa.*

2.2.2 System boundaries and limitations

For all three systems the included operations were examined, from where the slash were lying at roadside, to when it was processed into hog fuel and was delivered at the industrial yard. This meant that analysis of the Slash-system ended when the slash had been grinded, of the Hog fuel-system when the trucks had dumped their load directly in or in the vicinity of the industry's dump pocket. The analysis of the Bundle-system was ended when bundles had been grinded.

Both vigorous and beetle infested biomass was considered as feedstock in the study, although mainly aiming at fuel recovery from conventional final fellings (i.e. where the main proportions of the biomass can be recovered as saw logs or pulp). This study does not approach conditions of a specific location, but applies generally to sites in the interior of B.C. where the alternative treatment would be pile burns. The Interior forests generally imply pine-dominated blocks of smaller trees and with lower volume than the coastal forests.

This study did not address the profitability of using the roadside slash in a particular system due to the uncertainty of price that potentially could be received for the delivered biomass. The study was delimited to the processing and road transports, while a full system analyze of profitability would comprise the full chain of handling, from final felling to end-users consumption.

2.2.3 Costs, fuel consumption and CO_2 emissions

Currency figures in this report are expressed in Canadian dollars with the base year in 2008. Costs from the literature have been adjusted to the year 2008 using the Consumer Price Index and historical inflation rates declared by Bank of Canada (Bank of Canada, 2008).

The fuel costs of all machineries were based on the diesel cost $1.40/liter. All the used machinery was assumed placed on contractors and was applied an hourly rate (table 1), in which maintenance and amortizing costs of machineries are incorporated (Canadian experts, 2008). Consequently, machinery was assumed leased on hourly basis, irrespective of allocation or performing work operations. The grapple loaders and wheel loaders were considered already on site, as they were assumed used in the prior final felling. The cost rate in the case where the grinder is powered by electricity was set with intention to reflect the relatively low cost of electricity in B.C.

The total cost per owen dry tone of biomass (Odt) at landing of a system was calculated by adding the cost of the included machinery. Hence, equations 1-3 were used for calculating the total cost of, respectively, the Slash-system ($C_{Tot(SL)}$), the Hog fuel-system ($C_{Tot(HF)}$) and the Bundle-system ($C_{Tot(B)}$).

$$C_{Tot(SL)} = C_{GL} + C_T + C_{GR} \quad [1]$$

$$C_{Tot(HF)} = C_{A(GR)} + C_{GL} + C_{GR} + C_W + C_T \quad [2]$$

$$C_{Tot(B)} = C_{A(B)} + C_B + C_T + C_{GR} \quad [3]$$

In Eq. 1-3 C_{GL} is the cost for the grapple loader, C_T is the cost for road transports, C_w is the cost for the wheel loader and C_{GR} is the cost for the grinder, $C_{A(GR)}$ and $C_{A(B)}$ is the costs to allocate the grinder respectively the bundler to roadside and back and C_B is the cost for the bundler. The cost calculations for different machinery are presented below (Table 1).

Table 1. Machinery cost rates, fuel consumption and CO_2-emissions used in the analyses

Tabell 1. *Maskinernas timkostnader, bränsleförbrukning och koldioxidutsläpp*

System	Machinery	Hourly rate ($/h)	Fuel consumption (l/h)	Fuel consumption (kg/h)	CO_2-emissions (kg/h)
Slash	Grapple loader	104	26	21.3	66.4
	Trucks	135	40	32.7	102.1
	Grapple loader	104	26	21.3	66.4
	Grinder	300	0	0.0	0.0
Hog fuel	Allocation of grinder	335+135[a]	40	32.7	102.1
	Grapple loader	104	26	21.3	66.4
	Grinder	500	170	139.1	433.9
	Wheel loader	110	20	16.4	51.0
	Trucks	135	40	32.7	102.1
Bundle	Allocation of bundler	230	30	24.5	76.6
	Bundler	230	30	24.5	76.6
	Trucks	135	40	32.7	102.1
	Grapple loader	104	26	21.3	66.4
	Grinder	300	0	0.0	0.0

[a] Hourly rates for the grinder and for the truck transporting the grinder on a lowboy trailer is 335 $ and 135 $, respectively.

Calculated CO_2-emissions were based on the fossil fuels used during handling, processing and transporting slash within the stated system boundaries. CO_2 is not the only green house gas causing climate change, although it was considered a relevant parameter to evaluate in this study. The density of diesel (class 1) is 0.818 kg/liter, the heat value is 0.0098 MWh/liter (9.8 MWh/m^3) and each liter diesel discharge 2.55 kg of CO_2-emissions to the atmosphere (Naturvårdsverket, 2008). Table 1 illustrates the amount of CO_2-emissions that the different machineries release every working hour.

No CO_2-emissions were accounted for the grinding in the Slash- and the Bundle-systems, as grinding in the stationary application were assumed powered by electricity generated by hydro or in any other CO_2-neutral manner.

2.3 *Biomass features*

2.3.1 Residual yield

With the present practice of pile burns, the conventional roadside piles in B.C. are of no oriented structure and can be difficult to handle. With slash as a commercial product, pile structure is important for high productivity in the supply chain (Andersson et al, 2002). The slash was therefore assumed piled up in a somewhat uniformed way, adapted for further handling and processing. According to interviewed operators of dangle head processors this should be possible by only slightly alter the current work methods.

The two most common conifers that are harvested for timber in Sweden are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). The yield of energy assortment in Sweden is generally higher the more spruce dominated the cut-block is, since Norway spruce tends to have a higher crown mass then the Scots pine. Crown mass is normally stated as the trees' proportion of crown mass in percent of the stem mass (Hakkila, 1989). Figure 1 shows some of the most common tree species to be found in B.C., with the different crown profiles indicating different residual yields. According to Hakkila (1989), Lodgepole pine (*Pinus contorta var. latifoia*) with a mean diameter in breast height (dbh) of 19 cm has a crown mass proportion of 17.3 %. The crown mass proportion of a Douglas fir (*Pseudotsuga menziesii*) of 21 cm in dbh is 18.2 %, while it for Western redcedar (*Thuja plicata*) of 22 cm in dbh is 35.1 %.

Figure 2. Common species crown profiles in B.C. From left: Lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), Subalpine fir (*Abies lasiocarpa*), Western hemlock (*Tsuga heterophylla*), Western redcedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*) (B.C. Government, 2008b).

***Figur 2.** Kronprofiler av vanligt förekommande trädslag i B.C. Från vänster: Contortatall (Pinus contorta), Douglasgran (Pseudotsuga menziesii), Berggran (Abies lasiocarpa), Jättehemlock (Tsuga heterophylla), Jättetuja (Thuja plicata), Sitkagran (Picea sitchensis) (B.C. Government, 2008b).*

One of the objectives in this study was to evaluate the bioenergy feasibility of the MPB-killed trees, it was therefore assumed that the slash has the features of lodgepole pine. The actual quantity of slash depends, however, on more than just the species composition of the cut-block. Site history has affected the forest's structure and present market conditions affects the minimum diameter harvested (Hakkila, 1989). The slash was assumed to keep the maximum diameter of 10 cm, which correspond to a final felling that has had 10 cm as the minimum diameter for their timber yield. According to Hakkila (1989), conifers' residual biomass from conventional Nordic final fellings equals at least 30 % of the stem volume for an even-aged cut-block on an average good site. Field measurements in central B.C. shows that 14-55 % of the original forest biomass was left as slash at roadside (MacDonald, 2006). Taking these aspects into account, it was assumed that the recoverable slash correspond to 30 % of the total harvested biomass volume. Using 250 m^3/ha as average merchantable volume in the Quesnel timber supply area (TSA) (MacDonald, 2006), the slash volume was equivalent to 75 solid m^3 per ha. This volume of mainly branches and tops was converted to mass by assuming that the solid slash had the same basic density as lodgepole pine stemwood (403 kg/m^3 (Forintek, 1977)). The comparison of systems was performed for slash amounts at landing that corresponded to different sizes of final fellings. By the described volume calculations it was assumed that a 10 ha final felling equals 302 owen dry tonnes (Odt) of slash, a 30 ha likewise equals 907 Odt slash, 60 ha equals 1814 Odt and 90 ha equals 2720 Odt.

2.3.2 Moisture content

The moisture content (m.c.) in green branches shortly after a final felling may vary widely, but is often between 40-60 % (green basis) depending on species, branch diameter, season and weather (Hakkila, 1989). In this study it has been assumed that the vigorous fresh slash's m.c. is 50 %. Woody debris that is left behind or in storage tends to reach equilibrium with its storage conditions. The equilibrium moisture content (EMC) is a function of ambient temperature, relative humidity, wind speed, season, precipitation, tree species and tree size. The EMC are therefore a factor that differs between each region and present conditions (Pettersson and Nordfjell, 2007; Kumar et al., 2007). Small piles naturally dry faster than big piles, although, they consequently also regain moisture faster (Pettersson and Nordfjell, 2007). When the m.c. of the stem decreases to below the fiber saturation point, the trunk may crack and become useless as lumber. Chow and Obermajer (2007) declare construction lumber requirements to be at the minimum 19 %, which match the data from saw mills in the West Fraser region that use timber of m.c down to 20-28 % as lumber (Andersson 2008, pers. com.). In this study it has been assumed that the m.c. of MPB-infested biomass is 25 %.

2.3.3 Energy content

Thermal energy actually recoverable from woody biomass depends on both effective heating value and m.c. High m.c. is detrimental in two ways. It reduces the available heat of the fuel, since there is less combustible matter per unit mass, as well as it reduces the effective heating value, since energy is required to raise the water temperature from the ambient degree to the boiling point and then to steam (Hakkila, 1989).

The calorimetric value (also called the heating value) per unit mass of fuel is higher in coniferous branches than in coniferous stem wood, since branches are rich in extractives as lignin and resin. Slash including foliage has a marginally higher heating value than slash without foliage, at least on mass basis. However, the low density of foliage actually reduces the heating value when measuring on volume basis (Hakkila, 1989).

The Wood Pellet Association of Canada has found that pellet made of MPB-infested biomass has a higher heating value than pellet made out of the normal feedstock, which was believed to be the result of trees' chemical defense mechanisms when they are attacked (Melin, 2008, pers. com.). However, since the difference appear to be marginal (5.07 MWh/Odt compared to 4.99 MWh/Odt), that aspect was excluded in the calculations.

The content of in-organic compounds is an important parameter when estimating the energy content of biofuels, since it is the source of ash. Ash content is defined as the total weight of all non-combustibles in relation to the total weight of the biofuel. Low ash content is desirable, as a high amount of in-organics has both a low gross calorific value (q. gross) and causes residue problems in burning equipments (Rhén, 2004). Naturally a dirty feedstock results in high ash content, no matter what material that is used. The biomass in this study though is assumed fairly clean, since there are site disturbance tolerance limits in the silvicultural prescriptions in B.C., limiting the harvest activities when the ground is soaked by rain (LaPointe 2008, pers. com.).

M.c. and ash content are often taken into account in the pricing of biomass for energy purposes, as the buyers calculate the energy content by an equation with reduction for these factors. At increased m.c. the recoverable energy, the net calorific value as received ($q_{net\ p.m.}$) (also called lower heating value), decrease according to:

$$q_{net\ p.m.} = \left(q_{net\ p.} - 2.45 \frac{MC}{100 - MC} \right) \times \frac{1}{3.6} \qquad \text{(MWh/Odt)} \qquad [4]$$

were $q_{net\ p.}$ is the net calorific value (i.e. effective heating value of dry biomass with energy losses due to ash content deduced) for the specific biomass expressed in GJ/Odt and *M.C.* is the moisture content, expressed in percent. The constant *2.45* represents the energy that is required to vaporize one tonne of water (in GJ/tonne) and the factor *3.6* converts GJ/Odt into MWh/Odt (Hakkila and Parikka, 2002).

The net calorific value ($q_{net\ p.}$), is rather stable for woody biomass, even though tree limbs and bark generally have a slightly higher value than stemwood. For lodgepole pine the net calorific value for oven-dry stem wood is 5.28 MWh/Odt (19.0 GJ/Odt) (Forintek, 1977), which is similar to the value for Scots pine 5.36 MWh/Odt (Hakkila and Parikka, 2002). For Scots pine the net calorific value for limbwood and whole tree is 5.55 and 5.41 MWh/Odt, respectively (Hakkila and Parikka, 2002). The exact mix between stem wood, bark and fines will vary from site to site and therefore it could only be assumed what the net calorific value ($q_{net\ p.}$) in this study would be, and it was set to 5.41 MWh/Odt (19.5 GJ/Odt). With those assumptions in equation 4, the resulting net calorific values as received at m.c 50 % and 25 %, were 4.74 MWh/Odt and 5.19 MWh/Odt, respectively. These values were used to calculate the total energy (table 2) that can be recovered over the four different simulated final felling cut-blocks.

Table 2. Cut-block size and the corresponding mass of slash and its energy content with a moisture content of 50 % and 25 %

Tabell 2. Hyggesareal och den motsvarande massan avverkningsrester och energiinnehåll för 50 % respektive 25 % fukthalt

Area (Ha)	Mass (Odt)	$MWh_{50\ \%}$	$MWh_{25\%}$
10	302	1 431	1 567
30	907	4 299	4 707
60	1 814	8 598	9 415
90	2 720	12 893	14 117

2.3.4 Bioenergy-adapted roadside piles

An important phase in the whole process of bioenergy-adapted harvestings is the formation of the roadside slash piles, which also are called windrows. The piles should be formed to allow defoliation, promote drying and prevent from water uptake during rain and snowmelt. The defoliation of needles and leaves not only support the preservation of nutrients to the site ground, but also reduces the ash content and increases the calorific values of the biofuel (Nordic Innovation Centre, 2008). Salvaged biomasses from the MPB-killed trees already have reached this state when they are piled at roadside.

By achieving decreased m.c. the transportation efficiency increases (as less water are transported) and the whole system gets "colder" in the sense that there are less "just-in-time" requirements due to the decreased susceptibility to value lowering determinants (e.g. mould and other biotic and abiotic exothermic processes).

The pile size naturally depends on the volume in the cut-block, but also by the predetermined minimal diameter that can go as saw logs and pulpwood. The minimal top diameter that are cut and processed as saw logs depends on primary two factors, the legal limit (minimum 10 cm) and the markets demand (may fluctuate from 7-12 cm) (LaPointe 2008, pers. com.) Available space at roadside may determine how the piles are oriented and distributed. The slash may be distributed into several smaller piles if space are available, which improves the drying and the litter drop (Nordic Innovation Centre, 2008). The preferable size stated in the Nordic Innovation Centre's guidelines is 20-30 meters length of at maximum 4 meters height. In this study it is assumed that the roadside piles are parallel to the road and in reach for the truck mounted bundler. Piles that are to be stored over seasons should ideally be covered by corrugated cardboard (available as 4×500 m rolls) and have the top section formed to enabling rain and melting snow to run off (Nordic Innovation Centre, 2008).

It is important that the site for storage of hog fuel is flat and has been cleared from obstacles in order to minimize dry matter losses (Nordic Innovation Centre, 2008). Storage of comminuted biomass is much more complex than uncomminuted biomass, since the material’s exposed surface is bigger. Pile size, m.c., dry matter loss and change in energy content are interrelated during storage and fluctuates over the year’s seasons (Hakkila, 1989). Fuel qualities of biomass processed into bundles are better preserved during storage than loose slash, which are easier remoistened during winter (Hakkila, 1989; Pettersson and Nordfjell, 2007).

2.3.5 Biomass forms and logistics

In this study different transportation systems have been evaluated with their central difference in load volume capacity at different processing levels of the slash. The effective heating value per cubic meter is therefore of crucial interest, where the biomass bulk density constitutes the conversion factor from mass to volume. The variation in biomass density among different tree species is considerably larger than the variation of effective heating value in dry mass. A high heating value per cubic meter is always a result of high biomass density (Hakkila, 1989).

Bulk density refers to the biomass weight divided by the biomass volume, with the unit oven dry tonnes per cubic meter (Odt/m^3) chosen for all systems’ irrespective of the biomass’ processing level. Estimates of bulk density reflect the solid content, which is a factor dependent on several parameters, such as biomass density, biomass orientation, biomass structure, stem diameter, compaction and m.c. (Hakkila, 1989).

Wood shrinks when it dries and the biomass occupies less space, but also does dry matter create more fines than raw material, which make the particle distribution more compact (Hakkila, 1989). Assumptions of the solid contents at different biomass forms and m.c. therefore have a direct impact on the dry matter volume capacities of the trucks. It was assumed that the load will be compacted by the loader’s crane and that the solid content of transported loose slash was 19 % and 20 % (Angus-Hankin, 1995) for 50 % m.c. respectively 25 % m.c. Solid contents of the hog fuel loads were set according to actual transports in the interior of BC, where 141 m^3 trailers had 24 % and 26 % solid content respectively for 50 % and 25 % m.c. (Barbosa 2008, pers. com.). Solid contents of bundles were based on Lindroos et al (manuscript), and were set to 42 % and 47 %, respectively.

The dry matter bulk density was obtained by multiplying the basic density of lodgepole pine (403 kg/m^3 (Forintek, 1977)) with the solid contents of each system and m.c. combination, according the table 3.

Table 3. Bulk densities and load weights of system and moisture content combinations

***Tabell 3.** Bulkdensiteter och lastvikter för system och fukthaltskombinationer*

System	Moisture content (%)	Raw weight (t/load)	Bulk density (Odt/m^3)	Oven-dry mass (Odt/load)
Slash	50	21.59	0.077	10.80
	25	15.11	0.081	11.36
Hog fuel	50	27.28	0.097	13.64
	25	19.65	0.105	14.77
Bundles	50	26.40	0.167	13.20
	25	19.80	0.188	14.85

2.4 *Machineries*

Productivity of the machines was based on the forestry time concepts of E_0-hours and E_{15}-hours. E_{15}-hours include delays shorter than 15 minutes, for instance when repairing equipment, while all delays are excluded in E_0-hours. All data on productivity in this study are given on basis of Odt/E_0-hours and with the assumption that all systems have the same proportion of effective work time.

2.4.1 Trucks

In the Nordic countries the cut-to-length system is prevalent and the bundles were initially meant to be transported on regular timber trucks (Andersson, et al., 2002). The most common truck configurations in Sweden are 7-axle truck and trailer combinations. However, as there is a risk that pieces fall off and cause traffic accidents (Johansson, et al., 2006), most transports are now done by the use of slash truck-trailers with solid bottom and sideboards around the load space (Ranta & Rinne, 2006).

The most common log truck in B.C. is the pole trailer. However, it was considered unsuitable for transport of bundles (MacDonald 2008, pers. com.) and hence a short-log truck combination (figure 3) was assumed more suitable. Normally road transport of short logs in B.C. is performed by an 8-axle b-train truck configuration, although, with their somewhat lower clearance these are unsuitable for the gravel roads and rough terrain of off-highway conditions (Barbosa 2008, pers. com.). In order to avoid a system of both off-highway trucks and on-highway trucks, this study focused on truck configurations with a clearance that enables transports of whole distance from roadside of the final felling to the end-user. It was also assumed that the loads would be limited by volume rather than weight, due to the biomass' low density, and therefore was a 7-axle combination considered reasonable. In this study it was assumed that the same type of truck configuration was used in all the systems and with only small differences in features. This truck configuration (figure 3) can take the occurring steep grades, the tight turning radiuses and the limited area for turning the truck around at forest landings (Amlin 2008, pers. com.).

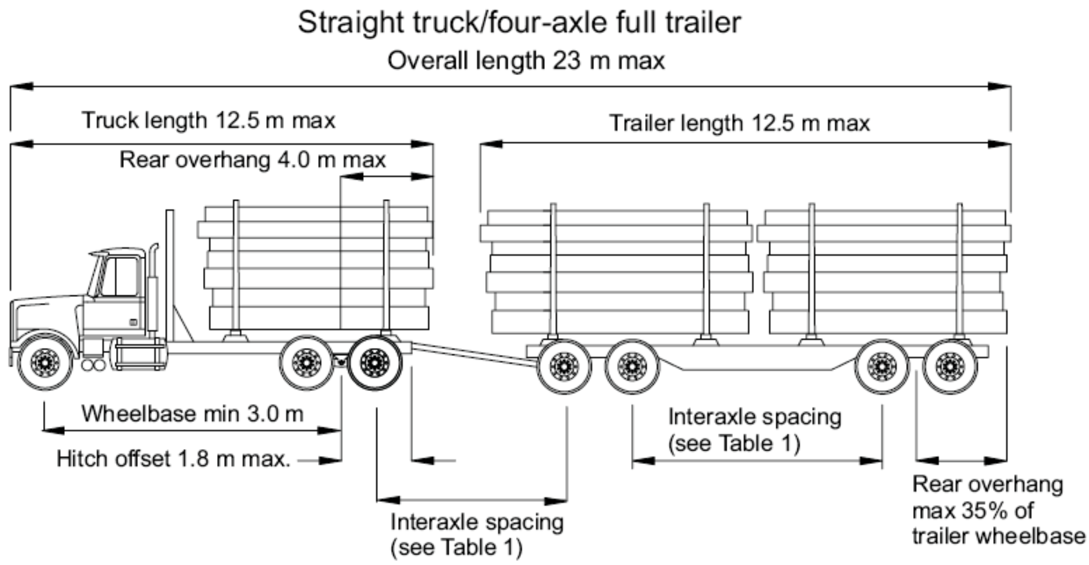

Figure 3. Principle dimensions of the in B.C. common short-log truck, which was used in the study with only slightly different assumed features for the three systems. Picture retrieved from: FERIC (2006a).

Figur 3. *Principskiss av en kort-stocks-lastbil som är vanlig i B.C. och som i denna studie används i alla tre systemen. Bilden hämtad från: FERIC (2006a).*

Further on in this report, truck combinations for transport of uncomminuted slash are referred to as *Slash-trucks*. Trucks used for transportation of hog fuel are referred to as *Hog fuel-trucks* and the trucks for transportation of bundles are similarly referred to as *Bundle-trucks*.

The hog fuel-trucks were, as common chip-trucks in Sweden, assumed to unload themselves to the side (figure 4). This study assumes that all biomass will be loaded on the trucks by a separate unit, a grapple loader available on site, which means that no crane mounted to the truck was required.

Figure 4. Hog fuel-truck able to tilt the bottom and unload to the side. Photo derived from internet: unknown source.

***Figur 4.** Hog fuel-truck med sidotippande botten. Bild hämtad från internet: okänd källa.*

Maximum weights and dimensions for on-highway vehicle configurations that transport logs in B.C. are restricted under the British Columbia Commercial Transport Act Regulations. Load restrictions depend on vehicle combination and design, e.g. axle configurations such as tandem or tridem drives, as it affects the tire loading and ground compaction (FERIC 2006a).

The maximum gross mass for the used truck configuration (figure 3) was 60 100 kg and as the total tare weight was assumed being 18 000 kg, resulting in a maximum payload of 42 100 kg. The payload was divided in relation to load space (FERIC 2006b) so that the maximal payload for the truck is 15 100 kg and for the trailer 27 000 kg.

However, the most typical settings of steer tires (model: 11R24.5) would actually only allow 38 588 kg and, hence, not the maximum payload (FERIC (a) 2006). However, this issue does not affect the studied systems, as the calculated loads (table 1) of the low-density material do not reach these limits. The raw weight per load and the oven-dry weight per load in table 3 were calculated by the bulk densities.

The maximum legal vehicle height in B.C. was 4.15 m and the average bunk height for this configuration was 1.35 m, which gave an available load height of 2.8 m. The common inside bunk width was 2.4 m (FERIC (b) 2006) and the truck's carriage length was assumed to 8.5 m, while the trailer length was 12.5 m. Consequently, for the hog fuel-truck and the slash-truck, the maximum available load volume was 141 m^3 (57.1 m^3 + 84.0 m^3). According to the load space dimensions and the dimensions of the bundles, the bundle-truck would fit three bundles in the base of each block. It fits three bundles in height, although it was assumed that it is possible to take two bundles extra per block on the top, making a total of 33 bundles for the three blocks (c.f. figure 1). As each bundle contained 2.5 m^3 (Lindroos et al, manuscript) the maximum payload volume was 84.6 m^3 of biomass.

2.4.1.1 Transportation

Estimated mean travel speeds (table 4) were based on truck's traveling times in the Quesnel TSA west of Fraser River (MacDonald, 2006), where also the LRDW (Land and Resource Data Warehouse) Road Network Database had been used to distinguish different road classes (Highway, Main road, Branch road and Spur road). In this study the prior data were extended to also include the transport distances 250 and 300 km. The new values were set by consideration to the relations between traveling times and distance in the prior data.

Table 4. Modeling distances and average speed at different road classes

Tabell 4. *Modellerade avstånd och genomsnittliga hastigheter för olika vägklasser*

		Transport distance (km)					
Road class	**Speed** (km/h)	50	100	150	200	250	300
Highway	80	10	33	52.5	74	97.5	120
Main road	60	10	27	52.5	76	97.5	120
Branch road	45	25	35	40	45	50	55
Spur road	20	5	5	5	5	5	5
One way travel time (h)		1.10	1.89	2.67	3.44	4.20	4.97
Total travel time, round trip (h)		2.19	3.78	5.34	6.88	8.41	9.94
Mean speed (km/h)		45.6	52.9	56.2	58.1	59.5	60.3

The cost of transportation depends on many factors, such as terrain, average speed and the contractors' machine cost. Therefore an hourly cost rate was assumed, where $135 was considered reasonable for these trucks (LaPointe 2008, pers. com.; MacDonald 2008, pers. com.). This number consider average values of operations over a period of time in mixed terrain and includes fuel consumption of about 40 liters/hour, driver's hourly wage of $30, contractor's costs for truck maintenance, mortgages and profit etc. This cost was set to both loaded transports, empty returns and to the time of waiting while loading as well. No difference was made between the loaded and empty transports mean traveling speed. The calculations account for that the exact amount of slash would be transported. Truck transportation costs per Odt (C_T) was calculated according to:

$$C_T = \left(\frac{M}{m_T} \times t_T \times c_T \right) \times \frac{1}{M} \qquad (\$/\text{Odt}) \qquad [5]$$

where M is the amount of slash in Odt at roadside, m_T is the payload of the truck in Odt for the given material (table 3), t_T is the time consumed (in hours) in each round of transport (table 4) and c_T is the hourly rate of the truck.

2.4.2 Grinders

A grinder was part of all three systems, either at the roadside or at the industrial yard. In both cases the horizontal grinder CBI Magnum Force 6800 (figure 5) has been assumed, although, with a modification in the latter case for a stationary application.

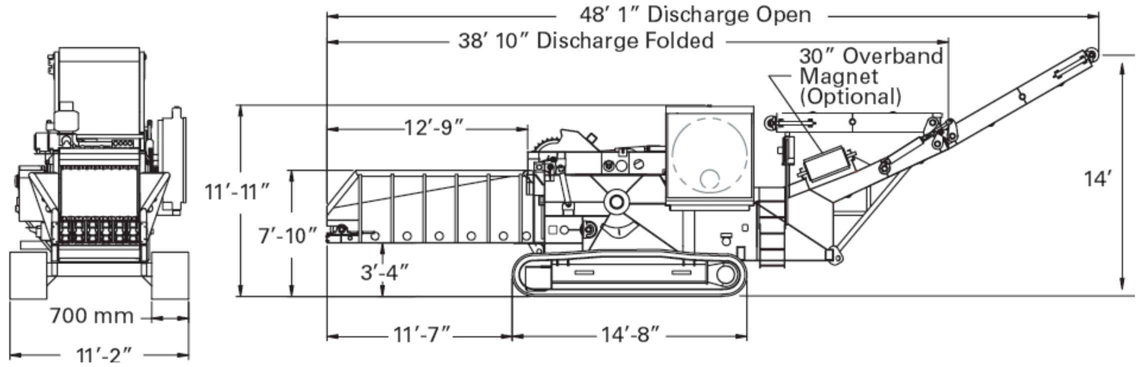

Figure 5. Schematic sketch of dimensions for the grinder CBI Magnum Force 6800, equipped with tracks. Photo derived from manufacture's website: CBI, 2008.

Figur 5. *Schematisk skiss med dimensioner för krossen CBI Magnum Force 6800, utrustad med band. Bild hämtad från tillverkarens hemsida: CBI, 2008.*

The motive to the choice of a horizontal grinder was its robustness and ability to comminute multiple feedstock forms and contaminated biomass (MacDonald, 2006). This was an assumed advantage at MPB-infested cut-blocks that have a high rate of trees non-recoverable as saw logs. In those cases the chosen grinder allows whole trees to be comminuted without a prior dangle head processing. A grinder at roadside may not be the most economical comminuting technique in all cases as it is likely to require both more space and fuel than a chipper would, but it adds flexibility for the feedstock choice. The 35 000 kg unit was transportable by a standard lowboy trailer (figure 6), although requiring a wide load-permit (CBI, 2008).

Figure 6. Transport of the grinder CBI Magnum Force 6800 on a Lowboy trailer configuration. Photo derived from grinder manufacture's website: CBI, 2008.

Figur 6. *Transport av krossen CBI Magnum Force 6800 på en Lowboy trailer. Bild hämtad från krosstillverkarens hemsida: CBI, 2008.*

The assumption of a fairly clean biomass implied a need of changing rotors to the model found in the 6400 series. If more contaminations are to be expected the 6400 series might be the better alternative altogether, since its interchangeable rotors give a higher tolerance to contaminations. However, the foremost incentive for the assumed choice of the 6800-series instead of the 6400-series, were the approximately $100 000 lower purchase cost (Heinrichs 2008, pers. com.).

The grinder's CAT C-27 (1050 hp) engine was assumed to consume 170 liter of diesel fuel (45 US gallons) per hour when fed by slash and logs (Heinrichs 2008, pers. com.). If working hard and if the operator manages to keep the in-feed full, the fuel consumption would be between 190 and 208 liters (50-55 US gallons) per hour. The latter consumption would possibly be the case for grinding of bundles, although, this study assumes the grinding at the end-user to be totally run by electrical power.

In a stationary application the grinder can be set up with twin 300 kW (400 hp) electric motors to drive the rotor, plus an additional 90 kW (125 hp) motor to drive the hydraulics. Generally the layout of the machine is the same, but with legs supporting the chassis instead of tracks (Heinrichs 2008, pers. com.). This configuration would in theory be possible to supply with power produced as a byproduct in a thermal station.

The grinders' productivity is in the ideal case 91 Odt/h (CBI, 2008). This factor is, however, determined and limited by the feeding capacity of the loader and how well oriented the piles of slash are, rather than the actual grinder. The productivity of the grinder and what have been used in the calculations was therefore equal to the assumed loader productivity (table 5). Hence, the utilization rate when grinding slash of 50 % and 25 % m.c. and bundles of 50 % and 25 % m.c. was 14.3 %, 15.0 %, 33.7 % and 38.0 %, respectively, of the possible grinding capacity. In the stationary application the utilization rates results in required energy inputs based on the effects of the electric motors (utilization rate×(300 kW+300 kW+90 kW)). The hourly required energy input to grind slash of 50 % and 25 % m.c. was, hence, set to 108.4 kWh and 113.7 kWh, respectively, with the corresponding required energy input for bundles being 255.5 kWh and 288.1 kWh, respectively.

The cost to operate in a stationary application was according to manufacture (and Swedish Experts, 2008) approximately half of the cost that was in a mobile application (Heinrichs 2008, pers. com.). In addition to the time consumed, the cost of a stationary application will also depend on the occurring price of electrical power, while the mobile application depends on the price of diesel. The manufacturer's experience was that the mobile application cost approximately \$500/h (Heinrichs 2008, pers. com.) and it was assumed that the hourly cost in the stationary application was \$300/h. Grinding costs (C_{GR}) per Odt was calculated according to:

$$C_{GR} = \frac{c_{GR} \times t_{GR}}{M} \qquad (\$/\text{Odt}) \qquad [6]$$

where c_{GR} is the cost per hour for the grinder, t_{GR} is the time consumed when grinding (hours) and M is the amount of slash (Odt) at landing.

Initial capital cost for a stationary electrical powered machine is generally more high, due to the initial electrical work that needs to be done, although, maintenance cost are significantly less than for the mobile diesel fueled machine (Heinrichs 2008, pers. com.). However, as defined by the constraints of this study, neither of those costs were to be determined here.

2.4.2.1 Grinding at roadside

The discharge of hog fuel was assumed to be into a pile on a flat and cleaned area along the road. In Sweden it is even common to cover the unloading area by a mat (vira from the wood processing industry) to further prevent the biomass from contaminations as sand and stones (Liss, 2006), although such measure was not included in this study. The hog fuel then needs to be loaded into the trucks, which was assumed done by the use of a wheel loader. No allocation cost was accounted for the wheel loader as it was assumed that the wheel loader had been used in the prior final felling and still was available on site.

However, the loading can be done in several alternative ways. The grinder could stand perpendicular to the road and discharge right into the waiting truck (figure 7), which require that the surrounding allow this space for the machines. Moreover, the grinding would be dependent on the truck fleet. Another alternative would be to discharge the hog fuel into a pile on the road and then let a truck fleet with mounted cranes load their own loads. The weight of the crane would constrain load capacity and it would be important that the entire pile is within reach for the crane.

Figure 7. Direct grinding into trucks, which not was assumed in the study but was an alternative way of loading hog fuel at roadside. Photo derived from MacDonald, 2007.

Figur 7. *Krossning direkt in i lastbilsflak är en alternativ lösning för lastning av krossmaterial i vägkant, dock ej antaget i denna studie. Bild hämtad från MacDonald, 2007.*

2.4.3 Bundler

The assumed bundler was the Swedish prototype Rogbico GTK 4800 (Rogbico AB, Sweden) studied by Lindroos et al. (manuscript). The bundling part was mounted to a Scania 580 truck (Scania AB, Sweden) and operated through the hydraulic power of the truck. The truck was equipped with an Epsilon 140L crane (Palfinger AG, Austria) and a Supergrip SG260R grapple (Hultdin System AB, Sweden) to feed the compressing chamber. The compressing force was 735 - 784 kN and it producing one bundle at the time. Three polyester cords (16 mm wide and 0.8 mm thick) wrapped the bundle, which then was unloaded from the chamber by the crane. The chamber's internal length, and consequently the maximum bundle length, was 4.8 m. The internal height was 0.95 m and the width was 2.1 m in top and 1.8 m in the bottom. Average diameter of the bundles was 0.8 m, making a volume of 2.4 m^3/bundle.

This machine was a prototype and the literature lacks data of productivity on lodgepole pine and at the specific m.c. All assumptions were therefore made based on a Swedish study (Lindroos, et al. 2008). The productivity was assumed 18.0 respectively 14.0 bundles per E_0-hour for m.c. 50 % and 25 %. The bundle weights will inevitably vary with the m.c. and thus the assumptions were made with consideration to that lodgepole pine's basic density is higher that the basic density of Norway spruce and Scots pine (Hakkila, 1989). The slash was also assumed to be of more stem wood than the Swedish slash. The raw mass was set to 0.80 and 0.60 tonne respectively, for the bundles of 50 % and 25 % m.c. with 0.40 Odt and 0.45 Odt as corresponding dry matter masses. No data were available, but based on the similarities with other machineries in this study, the fuel consumption was for the bundler set to 30 liters/hour and the hourly cost was set to $230. Bundling costs ($C_B$) was calculated according to the same equation principle as Eq. 3, but with the hourly cost and time consumption of the bundler.

2.4.4 Grapple loader

A grapple loader was assumed to feed the grinder and to load and unload the trucks. "Grapple loader" is a broad term and their design might be slightly different, but the basic principle was a separate and mobile unit with a crane to operate with. Being normally equipped with tracks the machine has a good mobility along the piles. It was furthermore assumed to be equipped with a debris grapple when feeding the grinder with loose material, which make rocks and contaminants falling through the open tines and also allow it to handle small materials efficiently (MacDonald, 2007). A normal log-grip can preferably be used when feeding the grinder with bundles.

The productivity data (table 5) were based on Swedish studies and were considered reasonable under the proposed B.C. conditions. It was assumed that the available space would limit the possibility to put in several loaders to feed the grinder and therefore were all calculations based on only one operating grapple loader. The assumed productivity might be somewhat optimistic numbers, although is important to achieve as it also limits the grinder's productivity in the Hog fuel-system. This aspect emphasize the importance of creating a well-structured roadside pile, so that the grapple loader easily can grip the slash and feed the grinder, or respectively, load the trucks with slash in the Slash-system. According to operators of dangle head processors, working with final felling processing in B.C. this would be possible to achieve with only a slightly different operating approach.

Fuel consumption and cost were set to 26 liter/hour and 104 $/hour, respectively (MacDonald, 2006). Operating cost for the grapple loader (C_{GL}) was calculated according to the same equation principle as Eq. 3, but with the hourly cost and time consumption of the grapple loader.

Table 5. Grapple loader productivity over operations, materials and moisture content

***Tabell 5.** Griplastarens produktivitet i olika arbetsmoment*

Operation	Material	M.c.	h/truckload	Odt/h	Source
Loading truck	Slash	50	0.83	13.01	Näslund 2006
		25	0.83	13.69	Näslund 2006
Loading truck	Bundles	50	0.43	30.70	Engblom 2007
		25	0.43	34.53	Engblom 2007
Unloading truck	Slash	50	0.30	35.99	Näslund 2006
		25	0.30	37.88	Näslund 2006
	Bundles	50	0.28	47.14	Engblom 2007
		25	0.28	53.04	Engblom 2007
Feeding grinder	Slash	50		13.01	Näslund 2006 [a]
		25		13.69	Näslund 2006 [a]
	Bundles	50		30.70	Engblom 2007 [a]
		25		34.53	Engblom 2007 [a]

[a] = derived from the source

2.4.5 Wheel loader

In this study a wheel loader refers to a tractor with front side loading arms. When using a wheel loader for loading of the hog fuel as in this study, the machine may serve several additional purposes, e.g. assisting the grapple loader when feeding the grinder and to clear the way and ease moving of the grinder, although the alternative usage were not accounted in this study.

It was assumed that the fuel consumption was 20 liters/hour, that the hourly cost was $110 (MacDonald, 2006) and that it took 20 minutes to load a hog fuel-truck, which equals 44.77 Odt/h and 49.94 Odt/h for m.c. 50 % and 25 % respectively. Operating cost for the wheel loader (C_W) was calculated according to the same equation principle as Eq. 3, but with the hourly cost and time consumption of the wheel loader.

2.5 Allocation

The allocation costs of the grinder and of the bundler were based on their hourly cost and the assumed time consumption. However, the grinder's hourly cost during transport was assumed being 33 % cheaper than when in operation, since the adjustable operational cost can be deducted. For the bundler, though, the hourly cost rate was the same for both allocations and for bundling work, since the same engine was used for the two work modes and it was assumed to work equally hard. Costs, time and fuel consumption was accounted for by the work elements pre-arrangements, transport to roadside, installation, transport arrangements and transport back to initial location. The pre-arrangements, installation and transport arrangements were assumed to take approximately 0.5 hours each (Heinrichs 2008, pers.com.). For the transport element, it was assumed that both allocation configurations kept the same mean travel speed as the trucks for transport of biomass (table 4). Likewise, the fuel consumptions were also based on the average hourly consumption for truck transport of biomass. For the grinder the allocation cost per Odt ($C_{A(Gr)}$) was calculated according to:

$$C_{A(GR)} = \frac{t_A\left(c_{A(GR)} + c_{T(GR)}\right)}{M} \qquad (\$/\text{Odt}) \qquad [7]$$

where $c_{A(Gr)}$ is the grinders cost per hour when transported, $c_{T(GR)}$ is the truck and trailer's cost per hour, t_A is the time consumed for allocation (hours) and M is the amount of slash at landing in Odt.

For the bundler the allocation cost per Odt ($C_{A(B)}$) was calculated according to the same equation principle as Eq. 3, but with the hourly cost (c_B) of the bundler and time consumption ($t_{A(B)}$) for one roundtrip according to table 4.

3 Results

3.1 Costs

For the two different moisture content levels, the trends are the same in terms of cost at certain slash amounts and transportation distances. The different m.c. of the feedstock principally just set different levels on the results.

The systems' cost per Odt of each work mode (allocation, transportation and processing) (Appendix 1) shows the dependencies of biomass amount and distance variation. When assessing the processing costs strictly by the actual processing (grinding, bundling and its necessary feeding), this mode shows independency of both alterations. Processing costs can thereby be seen as fixed costs that are independent of biomass amount and distance variation. Both transport and allocation costs are increasing with the distance but the transport costs are independent of the amount at landing, while allocation costs are decreasing with greater amounts. Transportation costs can, therefore, be seen as fixed costs when looking at different biomass amounts at landing at a given transport distance.

The Slash-system had the most economical processing (0 km in figure 8 A-H; Appendix 1). However, as soon as the biomass has to be transported, then there are several additional work phases to include in the processing costs, e.g. in the Slash-system: load the slash on trucks, trucks waiting while being loaded, trucks weigh-in and unload the residues. In each step where a loader loads a truck there are assembled costs of both the loader and the truck. Those costs are independent of biomass amount and distance variation and will, thus, add to the fixed costs. The Slash-system was somewhat competitive at short transport distances and small amounts of slash at landing, but was never the most economical system in total terms (figure 8 A-H). As the Slash-system not suffered from allocation costs, its total cost was directly dependent of the slash amount transported and comminuted. Hence, the cost per unit was constant irrespective of slash amount at landing (c.f. figure 8 A-H).

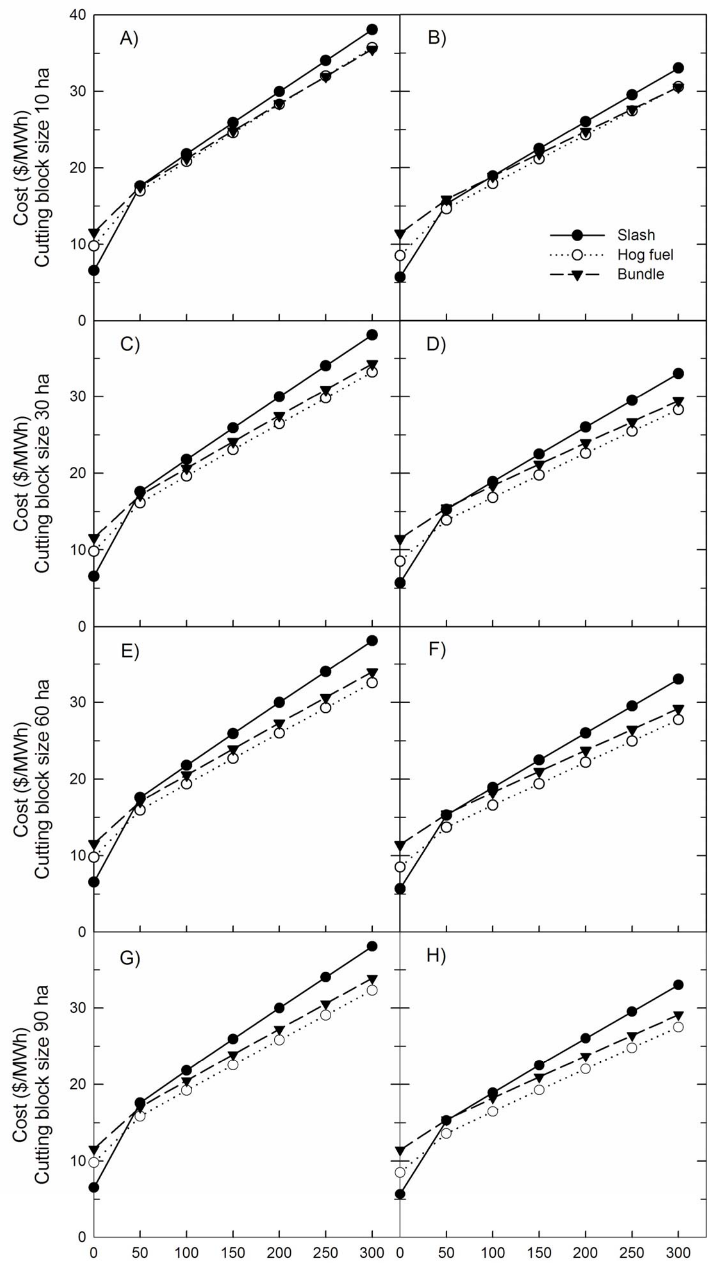

Figure 8 A-H. System cost comparisons for a moisture content of 50 % (left panes) and of 25 % (right panes) at different slash amounts at landing (cutting area sizes) as a function of transport distances.

Figur 8 A-H. *Jämförelse av systemkostnaderna för fuktkvoterna 50 % (till vänster) och 25 % (till höger) vid olika grot-mängder vid avlägg som funktion av transportavstånd.*

In almost all comparisons the Hog fuel-system was the most economic alternative and the Bundle-system was, likewise, the second best economic alternative. At the biomass amount corresponding to a 10 ha final felling (302 Odt) and a distance of 50 km the costs to process and transport hog fuel were 16.97 $/MWh (m.c. 50 %) and 14.62 $/MWh (m.c. 25 %). Due to the increased mean travel speed with distance (table 4), the total costs had a slightly declining increase and for the Hog fuel-system they were at 300 km 35.70 $/MWh and 30.59 $/MWh, respectively. However, at 250 km the Bundle-system became more economic and had at 300 km the total costs of 35.48 $/MWh and 30.55 $/MWh, respectively.

The compromise of low bundler productivity, a moderate load capacity (table 3) and a cheaper allocation cost than the Hog fuel-system, makes the Bundle-system some what competitive up to the intermediate slash amounts (30-60 ha) but is then outranged by the Hog fuel-system and its advantage of a greater load capacity. At great slash amounts the large number of truckloads required compensated for the Hog fuel-system's high allocation costs.

At a slash amount corresponding to a 30 ha (907 Odt) (figure 8 C-D) final felling the costs to process and transport hog fuel 50 km were 16.15 $/MWh (m.c. 50 %) and 13.88 $/MWh (m.c. 25 %). At 300 km these costs were 33.18 $/MWh respectively 28.30 $/MWh. At a slash amount corresponding to a 60 ha (1814 Odt) (figure 8 E-F) final felling the cost to process and transport hog fuel 50 km were 15.94 $/MWh (m.c. 50 %) and 13.69 $/MWh (m.c. 25 %). At 300 km these costs were 32.55 $/MWh respectively 27.72 $/MWh.

When there was an amount at landing corresponding to a 90 ha (2 720 Odt) (figure 8 G-H) final felling the cost to process and transport hog fuel 50 km were 15.83 $/MWh (m.c. 50 %) and 13.60 $/MWh (m.c. 25 %). At 300 km these costs were 32.30 $/MWh respectively 27.50 $/MWh.

3.2 CO_2-emissions

As for the cost evaluation, the different m.c. of the feedstock mainly just set different levels of the trends. The total CO_2-emissions in the Slash-system were increasing in direct proportion to the amount slash, and consequently the CO_2-emissions per MWh at a given transport distance was constant over slash amounts at landing (table 6). In general the Bundle-system resulted in least and the Hog fuel-system in the most CO_2-emissions per MWh (table 6).

Table 6. The systems' total discharge of carbon dioxide-emissions expressed in kg CO_2/MWh over all cutting block size (slash amount at landing) and transport distances

Tabell 6. *Total mängd utsläppt koldioxid uttryckt i kg CO_2/MWh fördelat på hyggesareal (GROT-mängd) och transportavstånd*

System	Moisture content	Object size (ha)	One way transport distance (km)					
			50	**100**	**150**	**200**	**250**	**300**
Slash	50 %	10	9.1	12.3	15.4	18.4	21.5	24.5
		30	9.1	12.3	15.4	18.4	21.5	24.5
		60	9.1	12.3	15.4	18.4	21.5	24.5
		90	9.1	12.3	15.4	18.4	21.5	24.5
	25 %	10	7.9	10.7	13.3	16.0	18.6	21.3
		30	7.9	10.7	13.3	16.0	18.6	21.3
		60	7.9	10.7	13.3	16.0	18.6	21.3
		90	7.9	10.7	13.3	16.0	18.6	21.3
Hog fuel	50 %	10	12.7	15.3	17.8	20.4	22.9	25.4
		30	12.5	15.0	17.5	20.0	22.4	24.8
		60	12.4	14.9	17.4	19.9	22.3	24.7
		90	12.4	14.9	17.4	19.8	22.2	24.6
	25 %	10	10.9	13.1	15.3	17.4	19.5	21.7
		30	10.7	12.9	15.0	17.0	19.1	21.2
		60	10.7	12.8	14.9	16.9	19.0	21.0
		90	10.6	12.8	14.8	16.9	18.9	21.0
Bundle	50 %	10	8.4	11.1	13.7	16.3	18.9	21.5
		30	8.2	10.8	13.4	16.0	18.5	21.0
		60	8.2	10.8	13.3	15.9	18.4	20.9
		90	8.2	10.8	13.3	15.8	18.3	20.8
	25 %	10	7.4	9.6	11.7	13.8	16.0	18.1
		30	7.2	9.3	11.4	13.5	15.5	17.6
		60	7.2	9.3	11.4	13.4	15.4	17.5
		90	7.2	9.3	11.3	13.4	15.4	17.4

3.3 Energy balance

The total energy consumption in relation to the harvested energy ranged from 3 % to 10 % (table 7). For all systems the biomass of m.c. 50 % required more energy-input than the biomass of m.c. 25 %. The Hog fuel-system was the system that required most energy-input, with approximately 7 % and 6 % respectively for the m.c. 50 % and 25 %. The Slash-system required slightly less energy input than the Hog fuel-system and the Bundle-system required least energy input.

Table 7. Total energy consumption in relation to harvested energy (%) over all cutting block size (slash amount at landing) and transport distances

Tabell 7. *Total energiförbrukning i relation till skördad energi (%) fördelat på hyggesareal (GROT-mängd) och transportavstånd*

System	Moisture content	Object size (ha)	One way transport distance (km)					
			50	100	150	200	250	300
Slash	50 %	10	4	5	6	7	8	10
		30	4	5	6	7	8	10
		60	4	5	6	7	8	10
		90	4	5	6	7	8	10
	25 %	10	3	4	5	6	7	8
		30	3	4	5	6	7	8
		60	3	4	5	6	7	8
		90	3	4	5	6	7	8
Hog fuel	50 %	10	5	6	7	8	9	10
		30	5	6	7	8	9	10
		60	5	6	7	8	9	10
		90	5	6	7	8	9	10
	25 %	10	4	5	6	7	8	8
		30	4	5	6	7	7	8
		60	4	5	6	7	7	8
		90	4	5	6	7	7	8
Bundle	50 %	10	3	4	5	6	7	8
		30	3	4	5	6	7	8
		60	3	4	5	6	7	8
		90	3	4	5	6	7	8
	25 %	10	3	4	5	6	6	7
		30	3	4	5	5	6	7
		60	3	4	5	5	6	7
		90	3	4	5	5	6	7

4 Conclusion / Discussion

4.1 Benefits and limitations of the study

B.C. is now in a situation where there are large quantities of biomass available from the MPB-infestation and a multitude of ideas for how to use it have been evoked. The biomass contains great amounts of energy and district heating along the Swedish lines are only one possible model to utilize this energy. The establishment of a wood fueled district heating system is obviously a major investment that not only requires new technique and infrastructure, but also further assessments of the available feedstock volumes and agreements about carbon credits disposition and distribution of generated heat and power. This study evaluated transportation techniques with the stipulated receivers being all kinds of forest residue users, such as thermal plants but also e.g. pellets producers. The most likely usage of slash and MPB biomass is for energy purposes and therefore economic comparisons was made in $/MWh, based on the conversion of the ingoing data in Odt/h.

One precondition of the study was to look at forests and forestry's role of mitigating climate change and therefore an evaluation of the three systems' levels of discharged CO_2-emissions was made. Carbon dioxide is not the only green house gas causing climate change, although it was considered a suitable measurement to use in this study.

Following the constraints of this study, as it aims for evaluation of systems that not yet are in practice, there are several unavoidable sources of possible variability and even inaccuracy. There are for instance the assumptions of solid content in roadside piles and on trucks, the costs of machineries, fuel consumption and the productivity. The difficulties to transfer machineries' costs and productivity from one region to another are induced by several fundamental differences influencing their performance, such as landscape characteristics, infrastructure and laws. However, the study was composed by the best available data in the literature and by information from interviews with experienced stakeholders and researchers. Due to the inevitable study constraints, the absolute costs levels might prove to deviate from ones in practical trials in BC. Nevertheless, this study should give a good indication of how the cost and emission levels of each system are related and how slash amount at landing and transport distance influence their competitiveness.

4.2 Costs and emission levels

The advantage of using the MPB-infested biomass is that there is less biomass required to generate the same amount of heat, since the net calorific value as received is higher in the biomass of m.c. 25 % than in the one of m.c. 50 %. Using a drier feedstock also increase the transport efficiency, decrease the costs and improves the emission discharge level.

At shorter distances the total cost is mainly depending on the cost efficiency of processing, while at longer distances it is the allocation costs and the difference in truckload capacity that affects the total cost and the competitiveness most. The costs have a somewhat declining increase illustrated in figure 8 A-H, which is due to the increasing mean travel speed with longer transport distances. The mean travel speed is a crucial parameter for the transport costs as there was an hourly rate applied for the trucks. At small amounts the time of allocating the machinery is relatively big, i.e. the non-operating hours constitute a large proportion of the work time that the machinery is leased. Thus, it is very expensive to recover small slash amounts over long distances if machinery has to be allocated to the roadside. However, if the machinery is allowed to work on big slash amounts, then the allocation cost per produced unit drops quite rapidly.

The competitiveness for the Slash-system is more dependent on the slash amount rather than the distance, which is mainly because the system does not require an allocation of expensive machinery. On the other hand, the bulkiness of the slash assign the inefficient loading and unloading, leading the system to long total time consumption. Another big shortage for the Slash-system is the slash-trucks' low load capacity. Every slash-truck can only take 79 % respectively 82 % of what the hog fuel-trucks and the bundle-trucks can take. This means that the bigger the amount of slash gets, the bigger is the difference in number of truck-runs between the Slash-system and the others.

The hog fuel-trucks' relatively high load capacity was a big advantage for the Hog fuel-system. However, due to the high hourly cost of the grinder, the Hog fuel-system generally needs a fair amount of slash at landing to become competitive. The grinder that was considered in this study is very powerful and productive machinery, although, it cannot be fully utilized with the presented settings as the grinder is limited by the loader's feeding capacity. If the loader's productivity could be increased, the grinder's capacity would be better utilized and requiring less processing hours, which would render the system to be more cost-effective. Additionally, the fuel consumption, and subsequently also the CO_2-emissions, would be lowered by the less required hours to operate. The Hog fuel-system replaces the requirements of comminuting techniques at the end-user, which would be a big advantage if the receiving end-user has limited space. The system also delivers a feedstock that does not allow long-term storage, which actually might fit with the system's benefit with storage space limitation (i.e. fast industrial consumption of small stock volumes).

An advantage for the Bundle-system compared to the Hog fuel-system is the lower allocation cost in combination with the cheaper grinding once at the end-user. This was evident in figure 8 A-B as the Bundle-system was the most economic alternative when the slash amount was small and the transport distance long. It should also be easier to feed the comprised units than the loose slash. More biomass can be fed into the grinder at the time, even though a somewhat lower conveyor speed might be required (Heinrichs 2008, pers. com.). An additional advantage for the Bundle-system in the grinding process, which also results in a benefit in total terms, is that the stationary grinding is considered to be powered by electricity and therefore do not discharge any CO_2-emissions to the atmosphere. This is of course on the condition that the electricity is generated in a CO_2-neutral manner.

Compared to the current B.C. oriented study, previous Swedish studies show higher transport costs. Englblom (2007) analyzed the costs of transporting slash of 50 % m.c. in Sweden and found the costs for a Slash-system to be 25.7 $/MWh for a transport distance of 100 km (exchange rate: 1$ = 6.04 SEK (Bank of Canada, 2008)). This tallies reasonably with data from a forestry company in Northern Sweden, which estimated their costs to 26.8 $/MWh for the Slash-system and to 26.0 $/MWh for the Hog fuel-system at a transport distance of 100 km and 50 % m.c. (Swedish Experts, 2008). For a newer version of the truck mounted bundler than the one in this study (producing longer bundles (5.1 m)), it has been found that the cost of bundling and comminution of bundles with a m.c. of 45% in Northern Sweden was 18.0 $/MWh at transport distances of 100 km (Edman, manuscript). The aspect of the amount of slash at landing has not been considered in the above Swedish cost calculations, but it is worth to note that the Bundler-system was the most and the Slash-system was the least competitive system. Irrespective of cutting block size the costs estimated for B.C. were always lower compared to the Swedish costs at this transport distance, with an exception for the Bundle-system. At a transport distances of 300 km the cost in Sweden was 33.3 $/MWh for the Bundler-system (Edman, manuscript), which align well with the estimated costs at greater slash amounts in the current study.

Differences between the current and previous analyses are likely due to a combination of differences in conditions between B.C. and the Nordic countries and to different input in the system analyses (e.g. approaches of estimating mean travel speed, productivity, allocation costs and hourly rates). Even though profitability was not targeted in this study, the comparison with the Swedish conditions gives some valuable indications. The price of comminuted biomass delivered to industry varies depending on season (demand) and supply, but was at the time for this study circa 33 $/MWh in Northern Sweden. Consequently, the Swedish cost at a transport distance of 100 km corresponded to 81%, 79% and 55% for the Slash-, Hogfuel- and Bundle-system, respectively. To maintain the same cost-income relation in B.C., the required price would be at least 26 $/MWh.

4.3 Future work

Wood based industries such as pellet factories and thermal power stations are of practical reasons often located in the immediate vicinity of a community where available land for storage and comminuting often is limited by the competition of area. With increased urbanization and competition for valuable land may the trend of biomass delivery possibly go towards more comprised material, which reduce the need of space for storage and comminuting equipment. In that case could the Slash-system possibly see a drawback, or at least be more likely to be used only between the forest roadside and a terminal. At the terminal could biomass be processed and transported to the end-user when the demand is right. However, if terminals are established and the grinder has to be fueled by diesel, then both the processing costs and the CO_2-emission discharge would be higher than in this study.

If replacing the grinder for a chipper when comminuting at landing or at terminal there would most likely be a lower fuel consumption, lower CO_2-discharge and lower costs for the comminuting and allocation as chippers normally are smaller machineries of lower productivity. To fully reach the benefits of using the highly productive CBI grinder, as for instance in the Hog fuel-system in this study, requires a great amount of slash and maybe more loaders, bigger ones or just other solutions for the feeding. The grinder's feeding though, could possibly be better off at a terminal where there is more space and easier to keep a firm and effective feeding.

The bundler's low productivity is of course a disadvantage, although it should be considered that the bundler assessed in this study still is a prototype. The reasons to bundle are to reach increased densities and create a standard unit that can be efficiently handled, which gives large handling and logistics advantages. Bundling also reduces susceptibility for growth of fungi in the biomass and minimizes deterioration of the biomass (Forsberg, 2000). However, the described logistic advantages cannot fully be utilized when the trucks' volume restrictions limits the payload, which is even more so when the m.c. decrease. Therefore, one could argue, is it reasonable to believe that the bundler's productivity and the bundle-trucks' load capacity could be significantly improved by adjusting the bundles' size. With such improvements the Bundle-system could become a system that is economically competitive in a broad range of slash amounts at landing and transport distances and also favored by its strong green incentives, i.e. low levels of CO_2-emissions.

The fuel consumption of the loader was in this study assumed according to MacDonald (2006), however, this parameter is crucial both for the cost and emission analysis and should preferably be further focused on in future research. Success in lowering the fuel consumption results in both lower costs and CO_2-emissions. It is recommended that further studies on this topic should be directed towards practical pilot evaluations of the systems, also with an evaluation of a terminal approach and a specific location of an end-user. With a specific location the conditions can be better defined and both available volumes and transportation costs can be estimated with a better precision. In such a study can also the biomass be better characterized and its suitability for e.g. bundle processing can be assessed.

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Appendix 1. Costs ($/MWh) for the transporting (T), processing (P) and allocation (A) work elements over systems, moisture contents (m.c.), size of final felling (i.e. slash amount at landing) and transport distances (one way)

Bilaga 1. *Kostnaden* ($/MWh) *för transport (T), upparbetning (P) och flytt av maskiner (A) för system, fukthalt (m.c.), mängd hyggesrester och transportavstånd (enkel väg)*

Final felling size	System	M.c.	Transport distance																	
			50 km			100 km			150 km			200 km			250 km			300 km		
			T	P	A	T	P	A	T	P	A	T	P	A	T	P	A	T	P	A
10 ha	Slash	50%	11.1	6.6	0.0	15.3	6.6	0.0	19.4	6.6	0.0	23.4	6.6	0.0	27.5	6.6	0.0	31.5	6.6	0.0
		25%	9.6	5.7	0.0	13.2	5.7	0.0	16.8	5.7	0.0	20.3	5.7	0.0	23.8	5.7	0.0	27.3	5.7	0.0
	Hog fuel	50%	7.3	8.5	1.2	10.6	8.5	1.7	13.8	8.5	2.2	17.1	8.5	2.7	20.3	8.5	3.3	23.4	8.5	3.8
		25%	3.7	9.8	1.1	6.5	9.8	1.6	9.3	9.8	2.0	12.0	9.8	2.5	14.7	9.8	3.0	17.4	9.8	3.4
	Bundle	50%	5.5	11.4	0.6	9.0	11.4	0.8	12.3	11.4	1.1	15.6	11.4	1.3	18.9	11.4	1.6	22.2	11.4	1.8
		25%	3.8	11.6	0.5	6.5	11.6	0.7	9.3	11.6	1.0	12.0	11.6	1.2	14.7	11.6	1.4	17.3	11.6	1.7
30 ha	Slash	50%	11.1	6.6	0.0	15.3	6.6	0.0	19.4	6.6	0.0	23.4	6.6	0.0	27.5	6.6	0.0	31.5	6.6	0.0
		25%	9.6	5.7	0.0	13.2	5.7	0.0	16.8	5.7	0.0	20.3	5.7	0.0	23.8	5.7	0.0	27.3	5.7	0.0
	Hog fuel	50%	7.2	8.5	0.4	10.6	8.5	0.6	13.8	8.5	0.7	17.0	8.5	0.9	20.2	8.5	1.1	23.4	8.5	1.3
		25%	3.7	9.8	0.4	6.5	9.8	0.5	9.3	9.8	0.7	12.0	9.8	0.8	14.7	9.8	1.0	17.4	9.8	1.1
	Bundle	50%	5.5	11.4	0.2	9.0	11.4	0.3	12.3	11.4	0.4	15.6	11.4	0.4	18.9	11.4	0.5	22.2	11.4	0.6
		25%	3.8	11.6	0.2	6.5	11.6	0.2	9.3	11.6	0.3	12.0	11.6	0.4	14.7	11.6	0.5	17.3	11.6	0.6
60 ha	Slash	50%	11.1	6.6	0.0	15.3	6.6	0.0	19.4	6.6	0.0	23.4	6.6	0.0	27.5	6.6	0.0	31.5	6.6	0.0
		25%	9.6	5.7	0.0	13.2	5.7	0.0	16.8	5.7	0.0	20.3	5.7	0.0	23.8	5.7	0.0	27.3	5.7	0.0
	Hog fuel	50%	7.2	8.5	0.2	10.6	8.5	0.3	13.8	8.5	0.4	17.0	8.5	0.5	20.2	8.5	0.5	23.4	8.5	0.6
		25%	3.7	9.8	0.2	6.5	9.8	0.3	9.3	9.8	0.3	12.0	9.8	0.4	14.7	9.8	0.5	17.4	9.8	0.6
	Bundle	50%	5.5	11.4	0.1	9.0	11.4	0.1	12.3	11.4	0.2	15.6	11.4	0.2	18.9	11.4	0.3	22.2	11.4	0.3
		25%	3.8	11.6	0.1	6.5	11.6	0.1	9.3	11.6	0.2	12.0	11.6	0.2	14.7	11.6	0.2	17.3	11.6	0.3
90 ha	Slash	50%	11.1	6.6	0.0	15.3	6.6	0.0	19.4	6.6	0.0	23.4	6.6	0.0	27.5	6.6	0.0	31.5	6.6	0.0
		25%	9.6	5.7	0.0	13.2	5.7	0.0	16.8	5.7	0.0	20.3	5.7	0.0	23.8	5.7	0.0	27.3	5.7	0.0
	Hog fuel	50%	7.2	8.5	0.1	10.5	8.5	0.2	13.8	8.5	0.2	17.0	8.5	0.3	20.2	8.5	0.4	23.4	8.5	0.4
		25%	3.7	9.8	0.1	6.5	9.8	0.2	9.2	9.8	0.2	11.9	9.8	0.3	14.6	9.8	0.3	17.3	9.8	0.4
	Bundle	50%	5.5	11.4	0.1	9.0	11.4	0.1	12.3	11.4	0.1	15.6	11.4	0.1	18.9	11.4	0.2	22.2	11.4	0.2
		25%	3.8	11.6	0.1	6.5	11.6	0.1	9.3	11.6	0.1	12.0	11.6	0.1	14.7	11.6	0.2	17.3	11.6	0.2

Appendix 2. Abbreviations, conversions and definitions

Bilaga 2. *Förkortningar, omvandling och definitioner*

Bone-dry = Oven dry = Dry = 0 % moisture content (m.c.)

Bulk volume = Volume of biomass including voids.

Bundles = Wood biomass, deriving from forest final fellings, which has been compressed and bound together with a lengthwise orientation. In literature also called cylindrical bales or composite residue logs.

Carbon-neutral = The carbon dioxide released when the biomass is converted to energy is equivalent to the amount absorbed during its' lifetime.

Dry matter = Biomass at basic density (0 % moisture content)

Dry weight bulk density = the bulk density of biomass when dry (m.c. 0 %)

EMC = Equilibrium Moisture Content. M.c over time as a product of ambient temperature and relative humidity.

Gross Calorific Value (Gross CV) = **(q_{gross}) =** Measure the amount of energy that maximally can be generated out of a specific material.

Heating Value = thermal energy content. The amount of energy released when a fuel is burned completely. Heating value depends on the m.c. and the phase of water going into steam.

Hog Fuel = Solid biofuel, derived from wood biomass, processed by crushing with the blunt tools of a "hog" - a mechanical grinder. Hog fuel ≠ Wood chips.

Moisture content = proportion of water in an item.

Moisture content on dry basis = The weight of water in an item divided by the weight of the dry matter, expressed as percent. (Sw. Fuktkvot = fria vattnets vikt/vikten av det torra materialet, inklusive det bundna vattnet (kan vara över 100 %)).

Moisture content on green basis = The weight of water divided by the total weight of the item, expressed as percent. (Sw. Fukthalt = vattnets vikt/trästyckets vikt.) Also called moisture content on wet basis. The only moisture content definition used in this thesis.

Net calorific value = **Effective heating value** = **($q_{net\ p.}$)** the amount of energy that can be generated from a specific material when no water is present.

Net calorific value as received = (q. net p.m.) = the energy that can be generated from a specific material with its present amount of water.

Oven-dry tonnes (Odt) = tonnes of dry matter

Roadside piles = Final felling biomass residues piled up at roadside.

Slash = Forest residues, low-value materials, resulting from commercial logging and silvicultural operations. May include tops, limbs, bark and whole trees.

Timber Supply Area (TSA) = An administrative tool for different geographic areas designated under Section 7 of the *Forest Act* (Ministry of Forestry and Range). Timber supply areas have an allowable annual cut set by the Chief Forester, which aims to provide a sustainable flow of timber to both replaceable and non-replaceable forms of volume-based tenures.

Wood chips = Solid biofuel, derived from wood biomass, processed by cutting with sharp tools of a chipper. Wood chips ≠ Hog fuel.