University of Alberta

The Techno-Economic Analysis of Biomass Transportation for Power Generation: Rail versus Truck

By

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Abstract

This study analyzes the economic and environmental effects of trans-shipping biomass from truck to train. Trans-shipment incurs incremental fixed costs, and there is a minimum shipping distance for rail transport above which lower costs per km offset the incremental fixed costs. The minimum economic shipping distance for straw exceeds the biomass draw distance, and hence the prospects for rail transport are limited to cases where traffic congestion from truck transport would otherwise preclude project development. In Alberta the layout of existing rail lines precludes a centrally located wood chip plant supplied by rail, while a more versatile road system enables it by truck.

A consolidated set of life cycle analysis data is used to investigate the environmental load for biomass trans-shipment from truck. The results favor train over truck. In addition, trans-shipment of biomass provides a means to limit the impact of road congestion and community resistance to large economic biomass projects.

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List of Abbreviations

CRF	Capital Recovery Factor
DFC	Distance Fixed Cost
DVC	Distance Variable Cost
g	Gram
GHG	Greenhouse Gas
HHV	High Heating Value
kg	Kilogram
km	Kilometer
l	Liter
LCA	Life Cycle Analysis
LHV	Low Heating Value
M	Million
m	Meter
MERSD	Minimum Economic Rail Shipping Distance
MJ	Mega Joule
MW	Megawatt
MWh	Megawatt Hour
NREL	National Renewable Energy Laboratory
RAC	Rail Association of Canada

Chapter 1

Introduction

1.1 Research motivation

Biomass for energy conversion is regarded as one of the most vital renewable resources in the future energy system. Biomass is stored solar energy and can be either changed to liquid fuel such as ethanol or be used in a combustion system (direct combustion or gasification) for the purpose of electricity generation. The limited future potential to import fossil fuels, arising from both potential political issues and the growing demand and associated increasing prices, and the accepted task to reduce Greenhouse gas (GHG) emissions (basically CO_2) are the two main motivators supporting the use of biomass. An increasing scarcity of fossil fuels will be an ongoing global issue in the next 50 years; this shortage will make this resource more and more valuable over time. Regardless of whether biomass is used either for conversion to fuel or combustion in power plants, bioenergy is definitely going to play a significant role in the future of the world's energy demand.

In comparison to all the fossil fuels biomass is very low in physical and energy density. Unlike coal and oil reserves the bulk of this resource is widely dispersed in forests and fields, often with a very low energy yield per unit area. Since the energy and physical density of the harvested biomass is very low, it always starts its journey on a truck. Due to all these facts bioenergy from field sources was usually regarded as a local resource and many biomass development schemes have been based on small scale processing. However many studies of biomass projects have discussed the tradeoff between rising transportation costs and higher capital efficiency as both project size and the draw area, i.e. the area from which biomass is sourced and transported to a processing plant, increase. These studies have shown that the optimum size of biomass projects is large when sufficient biomass is available (Dornburg and Faaij, 2001; Jenkins, 1998; Kumar et al., 2003).

Shipment of biomass faces two major problems: the high transportation cost per unit of contained energy and the road congestion that comes from the number of trucks used to supply an economically optimized large plant. This intensity of truck traffic may cause some community resistance in site selection for biomass processing plants. These two problems have led to a search for alternatives. Are there any other alternative methods of shipment? Are these alternatives less costly than truck transport? Do these new alternatives solve the road congestion problem? What are the environmental impacts of these different shipment methods? This thesis explores these questions for one alternate transportation mode, rail.

1.2 Research focus

An alternative to reduce transportation costs of biomass and also resolve the truck congestion problem is to offload biomass from trucks to an alternative shipment mode somewhere on the way to the plant. Pipeline transport of biomass has been evaluated in detail (Kumar et al., 2004). Slurry pipelining of biomass in water has a feasible cost structure at large scale for aqueous based processing, such as fermentation or supercritical gasification. However, this method is not desirable if the end usage is combustion, since the uptake of carrier fluid (water or oil) by the biomass is too high. The focus of this work is on offloading field harvested biomass including forest harvest residues (FHR, the branches, tops, and possibly stumps of trees harvested for pulp or lumber) and agricultural biomass, mainly straw, onto dedicated unit trains for shipment to large scale power plants. The cost of delivering straw and wood chips from FHR by trucks to rail terminals for further transport by unit train is compared to previous studies of power plants supplied by truck alone.

Another critical issue in comparing transportation by truck only to truck trans-shipment to rail is the environmental load of these two methods. A wide variety of data on emissions from rail and truck transport was integrated to develop a consolidated life cycle analysis (LCA) of emissions from truck only and truck plus train transport of biomass.

1.3 Research methodology

All modes of shipments can be analyzed in terms of unit cost, e.g. dollars per tonne, versus distance of shipment. This cost always includes two parts: a fixed cost of shipping a tonne biomass regardless of distance, which is called the distance fixed cost (DFC) and a distance variable cost (DVC) which includes fuel cost, labor cost and the capital recovery for the vehicles, equipment and facilities purchased. The distance variable cost is usually linearly proportional to the distance traveled, since speed of transport is often nearly constant. Hence in a trans-shipment of truck and rail each mode has both distance variable and fixed variable components. Making a cost model for the trans-shipment required identifying both components.

The cost model explained above was built up from a variety of sources:

- Truck costs including both the DFC and DVC are drawn from a detailed analysis of many previous studies of trucking costs (Kumar et al., 2004).
- In the rail case the DFC has two different parts. The first part is costs borne by the shipper who is responsible for loading the cars and hence owns the sidings and loading equipment. For a long term project the shipper owns the rail cars too. The second part is costs borne by the carrier who owns the tracks and engines (locomotives) and charges for the use of these. The carrier's fixed cost arises from the cost of dispatching a locomotive to pick up a train of rail cars; it is independent of scale as well as the distance of the haul. The shipper DFC is dependent on the scale of the project and in this study is calculated based on a specific size of power plant: 130 MW power plant burning chipped biomass from FHR (the size of this plant was determined to be optimal from a previous study (Kumar et al., 2003)), and a 250 MW power plant burning straw chopped from delivered large round or square bales with a

weight of roughly speaking 0.6 to 1 tonnes per bale. The straw power plant size is less than the optimum size, though the power cost vs. size profile is relatively flat between 250 and 450 MW and hence the impact of the smaller plant size is small (Kumar et al., 2003). The estimate of the rail carrier DFC and DVC was drawn from an analysis of budgetary quotes for moving straw and wood chips in western Canada provided by a carrier active throughout North America.

An idealized case is developed in this study to investigate the critical factors in trans-shipment of biomass, and then analyze two specific cases in the Province of Alberta, Canada using existing rail lines. A previous European study looked at transportation costs in Europe by truck, rail and ship (Borjesson and Gustavsson, 1996) and found that higher distances favored first rail, then ultimately ship transport. That study did not distinguish fixed and variable costs (a focus of this study), since recovery of incremental fixed costs of trans-shipment determine the minimum distance at which it is economic.

The research is built on two different analyses: first a detailed cost analysis on the rail trans-shipment of biomass and second an analysis of environmental impact. In the first part the comparison is based on the fact that any trans-shipment requires an incremental distance fixed cost at the point of unloading the biomass from trucks and loading it to the second mode. This incremental fixed cost can only be justified when the second distance variable cost is lower than that of the first mode. A key parameter is the distance at which the lower distance variable cost offsets the incremental distance fixed cost. If the rail haul distance of biomass is less than the distance required to recover incremental costs (DFC) of trans-shipment to rail, trans-shipment is not economic. LCA-based information on emissions from the two biomass transportation modes, rail trans-shipment and truck transport, is used to compare the environmental load of these two shipment alternatives.

1.4 Arrangement of the thesis

This thesis utilizes the authorized paper based format. Chapter 2 is based on a conference paper that has been submitted for publication in an technical journal. Chapter 3 is from a Society of Automative Engineers (SAE) Technical Paper prepared for a conference; future publication in a journal is planned.

Chapter 2 is a comprehensive study of the cost of rail trans-shipment of biomass. The study is based on the optimum plant size using straw and wood chips from FHR for a direct fired plant in Western Canada. A detailed comparison between rail trans-shipment and truck transport of biomass is included too. Appendix A shows the technical parameters used to build the transportation cost model. Appendix B contains a summary of the cost model used to calculate the transportation costs in different modes for various biomass types. Appendix C illustrates the methodology of finding the optimum number of trans-shipment terminals.

Chapter 3 presents an environmental evaluation for the rail trans-shipment and truck transport of biomass based on the published LCA results. For each transportation mode environmental emissions data are gathered from both Canadian and European sources. Using these data sets comparisons are done based on the mode of transportation and the origin of the sources.

A summary of this research work and recommendations for future research are contained in Chapter 4.

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Chapter 2

Rail versus truck transport of biomass*

2.1 Overview

Compared to solid and liquid fossil fuels, biomass is lower in energy density and physical density. Because field harvested biomass has a low energy yield per unit area compared to solid fossil fuel sources such as a coal, its initial transport is typically in a transport truck with a 20 to 40 tonne capacity. Each of these factors contributes to biomass having a significantly higher cost of transportation per unit of available energy than fossil fuels.

When biomass is transported all the way to its final destination by a transport truck, a further problem with road congestion may arise. Many studies have shown that the optimum size of biomass projects is large when abundant biomass is available (Dornburg and Faaij, 2001; Jenkins, 1998; Kumar et al., 2003). A detailed study of three field biomass sources in western Canada showed that optimum power plant size was 900 MW for biomass drawn from harvesting the whole boreal forest, 450 MW for straw, and 130 MW for forest harvest residues (FHR, the branches, tops, and possibly stumps of trees harvested for pulp or lumber); 450 MW is the largest assumed single unit size for boiler and steam turbo-generator in this study (Kumar et al., 2003). At 450 MW, biomass requirements are 2.1 M dry tonnes of biomass per year, equivalent to

* A version of this chapter has been submitted for publication. Mahmudi and Flynn 2005. Applied Biochemistry and Biotechnology.

one truck delivery of straw every 4 minutes if truck capacity is 17 tonnes of straw per load (typical straw trucks have a nominal capacity of 20 tonnes but are constrained by volume to carry about 17 tonnes per load). This intensity of truck traffic could lead to community resistance in site selection for biomass processing plants.

One alternative to try to reduce transportation costs of field harvested biomass and alleviate truck congestion is to offload biomass from trucks to an alternative transportation mode before delivery to the processing plant. Previous studies have evaluated pipeline transport of biomass in detail (Kumar et al., 2004; Kumar and Flynn, 2005); slurry pipelining of biomass in water has a feasible cost structure for aqueous based processing, such as fermentation or supercritical gasification. Biomass is not amenable to pipeline transport if the end usage is combustion, because uptake of carrier fluid by the biomass is too high.

In this work we evaluate offloading field harvested biomass onto dedicated unit trains for delivery to large scale power plants. The cost of delivering straw and wood chips from FHR by trucks to rail terminals for further transport by unit train is compared to previous studies of power plants supplied by truck alone. We develop an idealized case to explore the critical factors in trans-shipment of biomass, and then analyze two specific cases in the Province of Alberta, Canada using existing rail lines. A previous European study looked at transportation costs in Europe by truck, rail and ship (Borjesson and Gustavsson, 1996) and concluded that higher distances favored first rail, then ship transport. This study did not distinguish fixed and variable costs, a focus of this study, since recovery of incremental fixed costs of trans-shipment determine the distance at which it is economic.

2.2 Shipment of biomass by a single transportation mode

Many modes of transportation have a similarly shaped profile of cost versus distance shipped, as shown in Figure 2-1. The intercept of the line at zero distance, “a”, is the fixed cost of shipping a tonne biomass regardless of distance; we call this the distance fixed cost (DFC). For example, for trucking in North America a typical cost of loading and unloading a straw or wood chip truck is approximately $5 per tonne (Kumar et al., 2005). The slope of the line in Figure 2-1, “b”, is the distance variable cost (DVC). Most transportation modes have a linear DVC because the distance variable cost components, e.g. wages, fuel and capital recovery for the transportation equipment, are directly proportional to the distance traveled.

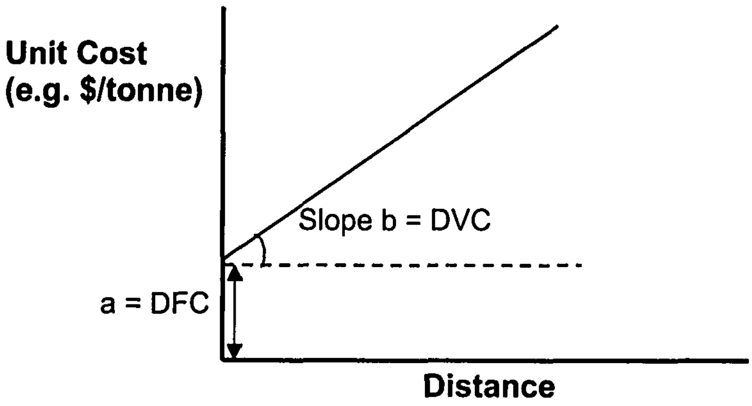

Figure 2-1. General plot of unit transportation cost versus distance showing distance fixed and distance variable cost.

Truck transport of biomass often requires little or no investment by the shipper, since trucks are owned by the carrier, not the shipper. Straw bales located at the roadside can be loaded on a straw transport truck by equipment located on the truck, and conveying of wood chips into chip trucks has a low fixed cost per tonne of wood chips. The situation is different for rail transport in North America: the rail carrier typically owns the main tracks but the shipper owns the siding and all equipment located there, i.e. the shipper is responsible for loading the railcars. In addition, for any long term project such as a power plant supplied by dedicated unit trains the shipper typically owns the railcars. Thus for rail transport of straw or wood chips, DFC has two components to it: the fixed cost charged by the rail carrier and the costs incurred by the shipper for loading the rail cars, including the rail siding and the railcars themselves.

Table 2-1 shows the values of DFC and DVC used in this study (all costs in this study are reported in 2004 US dollars). Truck costs are mid range values drawn from a detailed analysis of previous studies of trucking costs (Kumar et al., 2005). The estimate of rail carrier costs were drawn from an analysis of estimates for moving straw and wood chips in western Canada provided by a carrier active throughout North America (Johnson, 2004). Wood chips have an assumed moisture level of 45%, and straw an assumed moisture level of 16% (Kumar et al., 2003).

Table 2-1. Values of DFC and DVC used in this study

	Truck		Rail		
	DFC ($/dry tonne)	DVC ($/dry tonne-km)	DFC ($/dry tonne)		DVC ($/dry tonne-km)
			Shipper components	Carrier components	
Straw	4.76	0.1309	6.74	10.27	0.0277
Wood chips	4.98	0.1114	6.35	3.62	0.0306

Truck and rail carrier DFC is independent of scale, but the shipper component of DFC in Table 2-1 is calculated based on the "specific case" sizes in this study. The specific wood chip case is a 130 MW power plant burning chipped biomass from FHR; the size of this plant was determined to be optimal from a previous study (Kumar et al., 2003). The specific straw case is a 250 MW power plant burning straw chopped from delivered large round or square bales with a weight of approximately 0.6 to 1 tonnes per bale. The straw power plant size is less than optimal, but the power cost vs. size profile is relatively flat between 250 and 450 MW and hence the impact of the smaller plant size is small (Kumar et al., 2003). The wood chip power plant requires 3.8 unit trains per week, and the comparable figures for straw are 10.1 unit trains per week. For each of these cases a detailed scope of equipment required by the shipper is developed in order to estimate the shipper's component of DFC. In addition, we study a range of idealized straw and wood chip power plant sizes to estimate the size of power plant at which train transport is justified.

By inspection, rail shipment of biomass has a lower variable cost but a higher fixed cost; this is why most short haul of bulk goods is by truck and long haul by rail. However, the dispersed nature of biomass requires that it start its transportation to a processing plant on a truck. The critical issue for biomass therefore is under what circumstances it is economic to offload truck transported biomass to a train.

2.3 Trans-shipment: using two transportation modes

Because field sourced biomass must be hauled to a trans-shipment depot by truck, the total cost of shipment by truck and train is illustrated by Figure 2-2 At the point at which biomass is unloaded from the truck, point "x" in Figure 2-2, incremental DFC is incurred. This incremental fixed cost can only be justified if the DVC of the second transportation mode, in this case rail, is lower than that of the first mode, truck. The critical question for trans-shipment then becomes at what distance, "z" in Figure 2-2, does the lower DVC of the second transportation mode offset the incremental DFC? If the distance for rail shipment of biomass is shorter than "z", trans-shipment is not economic. Put another way, is the rail shipment distance far enough so that one can afford to offload biomass to a second transportation mode? In this study we refer to the distance "z" as the crossover distance, i.e. the minimum rail distance for which trans-shipment is economic.

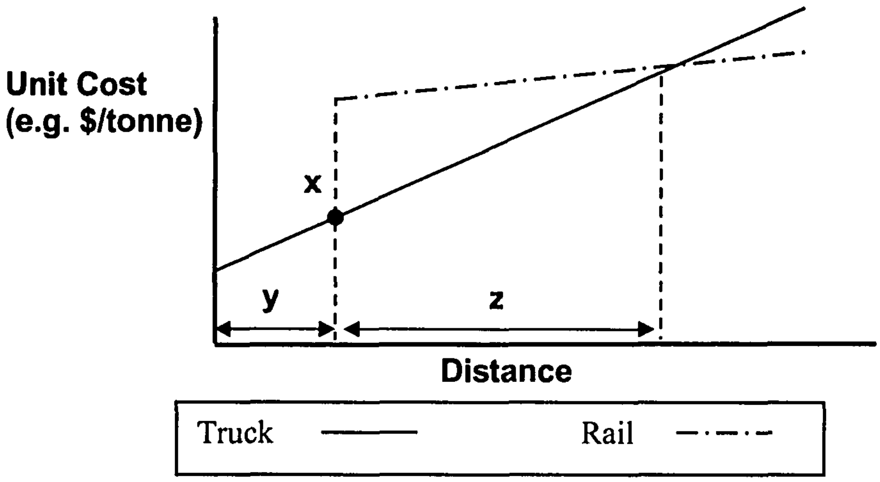

Figure 2-2. Unit transportation cost versus distance for truck only and truck plus rail.

Note that the distance "y" in Figure 2-2 is the average truck haul distance to the rail site. This is influenced by the number of trans-shipment points (in this study, rail sidings) that can offload the biomass. This is discussed further below.

2.4 Scope of equipment

2.4.1 Specific straw case

For truck only movement of straw, this study assumes that farmers place round or large square bales at roadside and cover them with tarps. The power company contracts with trucking firms to bring straw to the power plant, removing the tarps and leaving them at the roadside for reuse by the farmer. Trucks have self-loading equipment and are contracted year round, so that the annual harvest of straw is primarily stored on public road allowances at the sides of farmer's fields; in western North America road allowances are large and could store all of the straw harvest from adjacent fields. The power plant has at least one to two weeks of straw storage, and more if seasonal road access is an issue. Trucks are weighed on entry and exit from the plant, and straw moisture is measured; payments to the farmer are calculated on this basis. Straw is removed from trucks by fork lifts; a fleet of 18 is required (including one spare) for the specific case described above.

For trans-shipment of straw to trains, trucks arrive at existing designated grain elevator terminals and are weighed on entry and exit; straw moisture is measured at this time. Rental fees for land usage at grain terminals are based on discussions with industry (Simmons, 2004). Straw is stored until 2650 tonnes, an amount sufficient for a 100 rail car unit train, is amassed. Unit trains are dedicated to a single use, and not used for backhaul. Note that 100 car unit trains are standard for carrying grain and supplying coal to some power plants in North America, and that many (but not all) grain elevators have the capability to load 100 car unit trains; rates charged by rail carriers are lowest for 100 car unit trains with short turnaround times, i.e. loading times less than nine hours. Rail cars would be owned by the power plant through purchase or committed long term lease. Straw is loaded on the railcars in nine hours or less by a fleet of 18 forklifts located at each trans-shipment terminal. The operating crew for the forklifts rotates between the trans-shipment sites at grain elevators. When unit trains arrive at the power plant they are unloaded by forklifts; there is minimal difference in the requirement for forklifts and other equipment at the power plant between truck and truck plus train delivery of straw.

2.4.2 Specific wood chip case

In western Canada most trees that are harvested for pulp or lumber are skidded to the side of a logging road whole, and delimbed and topped at the roadside. Hence, FHR accumulates at roadsides as long windrows of material. A modified forwarder equipped with a pushing blade and a grapple would consolidate the residues and load the chipper. For truck only delivery of chips, trucks would normally be directly loaded from the chipper, but could also self load from wood chip piles. (Note that an alternative scheme would see residues rolled and bound and transported as "logs", a system developed in Finland for coniferous trees and applied to a variety of species in subsequent trials (Cuchet et al., 2004). (This system would require testing to determine its suitability for mixed hardwood and softwood stands found in western Canada.) Trucks would dump chips in the vicinity of dump pockets linked to a conveyor belts at the power plant. A bulldozer and front end loader would consolidate material at the power plant, and would move chips from long term plant site storage to the dump pockets if needed.

For trans-shipment of chips to trains, specialized sidings on existing rail lines in northern Alberta would be built, equipped with dump pockets and conveyor belts. Trucks would dump chips over the dump pockets; each siding would require a bulldozer and front end loader to consolidate chips. Chips would be accumulated until a full unit train could be loaded from multiple conveyors in nine hours or less. At the power plant rail cars would be rotated over dump pockets, a process currently in use with unit coal trains using gondola cars. There is minimal difference in the requirement for equipment at the power plant between truck and truck plus train delivery of wood chips.

Full equipment and staffing requirements were developed for each case, and capital and operating cost estimates were then calculated. Critical values for each "specific" case are shown in Table 2-2. Biomass yields are per gross hectare, which allows for uses of land in an area for purposes other than that associated with the biomass, such as communities, roads and alternate crops; details are in (Kumar et al., 2003). For straw we assume the power plant is able to purchase 80 to 85% of the available straw in the area in a poor harvest year (lowest quartile) and 60 to 65% in an average harvest year; note that a study has shown that recovery of straw does not reduce soil carbon in Canadian prairie black soils (Hartman, 1999).

Table 2-2. Cost factors for biomass transportation[a]

Fuel Type	Straw	Wood chips
Power plant size(MW)	250	130
Biomass yield (dry tonnes/gross ha)[b]	0.416	0.247
Biomass demand (Mdry tonnes/year)	1,180	635
Hectares required/year	2,830	77,100
Average driving distance (km)	67.2	350.3
Capital cost at the power plant ($ 000)		
Train cars[c,d]	28,500	16,000
Forklifts	418	-
Trailer buildings	45	15
Front end loader	-	30
Bulldozer	-	100
Building tracks at the plant	-	1,200
Operating cost for the power plant ($ 000)		
Salaries	1,400	500
Maintenance	318	170
Capital cost per rail trans-shipment terminal ($ 000)		

Forklifts	418	-
Trailer buildings	45	15
Front end loader	-	30
Bulldozer	-	100
Land for storage	-	23
Building tracks at the terminals	-	1,200
Mechanisms (Including conveyor belt, dumping system and dump pocket)	-	450
Operating cost per rail trans-shipment terminal ($ 000)		
Salaries	1,250	400
Maintenance	318	170
Rent for usage of facilities at terminals (Including land for storage)	150	-
Total capital cost ($ 000)[e]	29,700	22,700
Annual return on capital at 10%	3,210	2,410
Total operating cost ($ 000)[e]	4,730	1,410
Shipper component for rail DFC ($/dry tonne)	6.74	6.35

a – All costs in 2004 $ US. b – Gross hectares include all land, including land used for other crops/species, and for non-agricultural or forestry purposes such as roads, communities and industry. c – (Laver, 2004), d – (Nicholson, 2004), e – The capital and operating cost calculations are based on three rail trans-shipment terminals.

2.5 Idealized Straw and Wood Chip Cases

In evaluating truck only vs. truck plus rail shipment of biomass, we start with an idealized "best" case for straw and wood chips, in which rail sidings are assumed to be located exactly as needed in the center of contiguous sources of biomass, and rail lines direct from the sidings to the power plant are available. An idealized case defines a value of the crossover distance below which trans-shipment from truck to rail is not economic. If the number of trans-shipment terminals is optimized to give lowest overall biomass transportation cost, we call this crossover distance the minimum economic rail shipping distance (MERSD).

The first task is to determine the optimum number of trans-shipment points, i.e. railroad sidings that transfer biomass from truck to storage to train. There is an optimum, because a decrease in trans-shipment points increases the distance over which biomass is carried at the higher "per km" rate (DVC), i.e. it increases the distance "y" in Figure 2-2, while an increase in trans-shipment points increases the total DFC, because each siding requires a land payment and investment in loading and unloading equipment. The optimum number of terminal is that which gives a minimum total shipping distance, "y + z" in Figure 2-2, which corresponds to the minimum shipping cost. Figure 2-3 shows the calculated total shipping distance as a function of the number of terminals delivering straw and wood chips. From this we concluded that the optimum biomass shipment per rail terminal was approximately 255,000 dry tonnes per year. We tested this assumption with a larger straw fired power plant, 450 MW, and found a comparable result: shipping 225,000 dry tonnes of straw per terminal is the optimum tradeoff between truck DVC and rail DFC. A value of 255,000 dry tonnes of straw per year per terminal was used in the analysis of the idealized case.

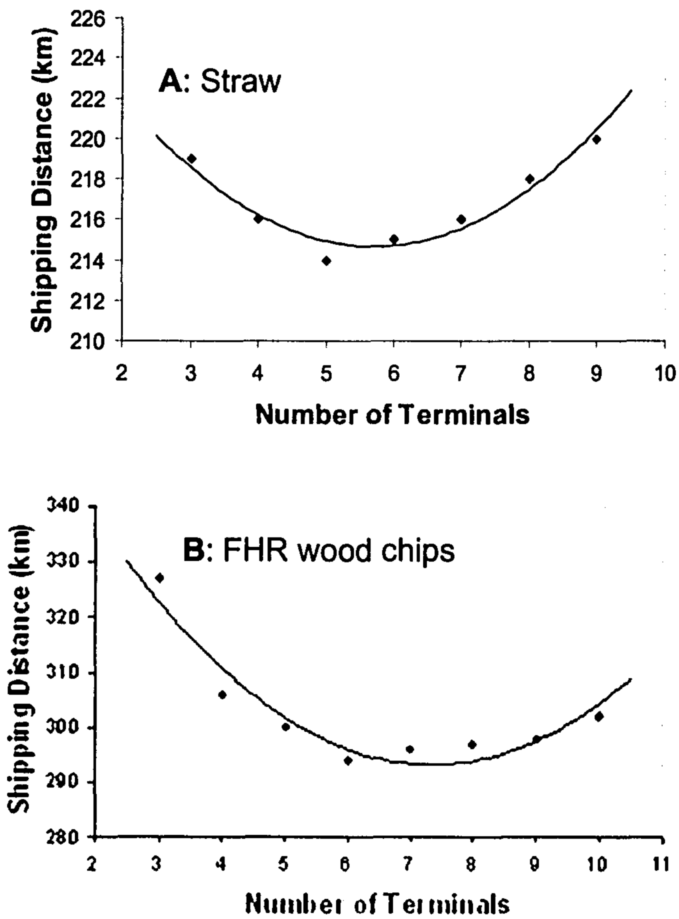

Figure 2-3. (A) Total shipping distance vs. number of rail trans-shipment terminals for a 250 MW straw power plant (B) and for a 130 MW wood chip power plant.

A similar analysis was done for an idealized wood chip case, and the minimum crossover distance corresponds to 100,000 tonnes of wood chips per terminal. This value was used in the subsequent development of the idealized case. Note that the optimum tonnes per year per terminal is lower for wood chips than for straw; this arises because the gross yield, i.e. the tonnes of biomass per gross hectare, is lower for FHR than for straw. Boreal forests have a long rotation cycle, typically 100 years in Alberta, Canada, and it is this low cutting frequency that gives a low net yield of FHR per gross hectare of forest. Hence to aggregate the same amount of biomass from chipped FHR a longer driving distance is required than for straw, and the optimum configuration of a two mode transportation system is less tonnage per rail terminal for a biomass source with lower gross yield.

Figure 2-4 shows the cost of delivered biomass in $ per tonne for truck only and truck plus rail shipment for the two cases. Note that the total shipping distance is 215 km for straw and the MERSD distance is 170 km for straw, and yet if centrally located a 250 MW straw power plant would draw from an area of radius of less than 100 km (the biomass draw distance) with an average driving distance of 70 km. The shipping and MERSD distances for straw are so much greater than the biomass draw distance that trans-shipment to rail is not economic at 250 MW for a centrally located straw power plant; there is not enough haul distance on rail to recover the incremental fixed costs of trans-shipment. Note that the calculated MERSD distance is consistent with current shipping practice in the grain industry: in discussion an Alberta based grain terminal manager noted that for single rail car quantities of grain (not a unit train) trucks are used to haul grain for distances up to 300 km, even if the truck route parallels existing train tracks (O'Brian, 2004). Shipment of biomass to a plant that is not centrally located to the draw area is discussed below.

For wood chips from boreal FHR the total shipping distance is 295 km and the MERSD distance is 145 km, while the biomass draw distance is 480 km, which gives an average driving distance of 340 km. Hence in an idealized case in which abundant rail lines are available it is more economic to transport boreal FHR wood chips by a combination of truck plus rail; the impact of the lower gross yield of biomass from FHR is to shift the optimum transportation mode to truck plus rail.

DVC for rail transport of straw is slightly less than DVC for rail transport of wood chips, because rail lines for forested areas of Alberta are more remote and presumably have higher maintenance cost. Despite this, the MERSD distance for hauling straw by rail is higher than for hauling wood chips, because the DFC for straw is higher: there is a larger cost in loading straw onto rail cars than wood chips, and a longer distance is required to recover this fixed cost. In general, determination of the minimum economic distance for trans-shipment requires a specific determination of DVC for both modes of transportation and DFC for switching from one mode to the other.

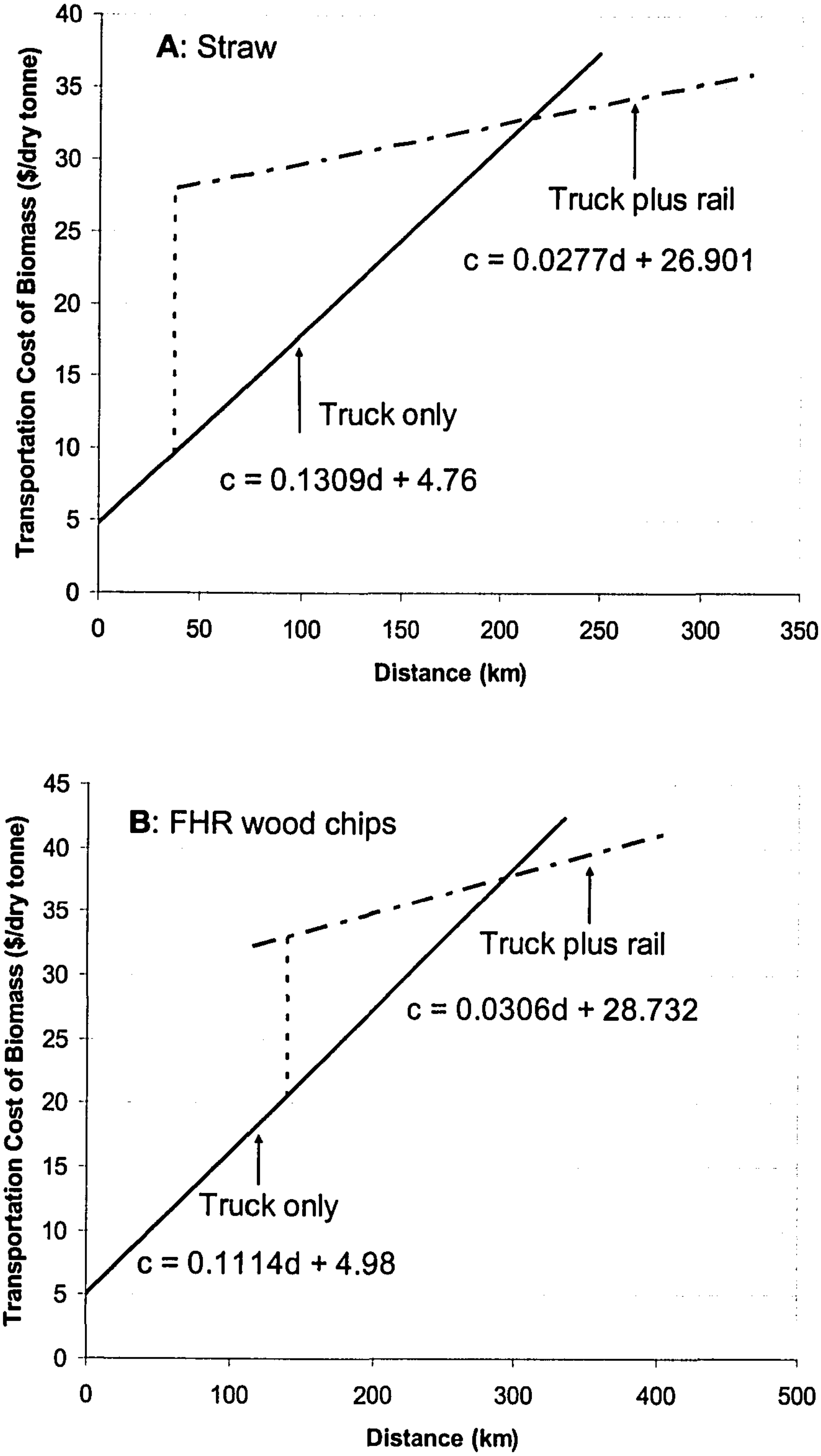

Figure 2-4. The cost of delivered biomass for truck only and truck plus rail shipment as a function of distance.

The size of the power plant determines the biomass draw distance; we analyze a range of plant sizes to determine the point at which, in an ideal case, trans-shipment to rail is more economic than truck only transport.

Figure 2-5A shows the total delivered cost of straw by truck only and by truck plus rail as a function of power plant size, assuming the plant is centrally located. Not until total plant size reaches 2700 MW does trans-shipment of straw to rail result in a lower delivered cost of biomass. Previous studies (Kumar et al., 2003) have shown that the optimum size of a straw power plant is in the range of 250 to 750 MW, and hence the practical potential for trans-shipment to give a lower biomass cost to centrally located power plants appears to be negligible. Even if straw yield is reduced by a factor of three, say because farmers are willing to sell less than 33% of recoverable straw to a power plant, transport by truck to a 250 MW centrally located power plant is more economic than truck plus rail transport. Figure 2-5B shows the comparable data for wood chips from boreal FHR. In an idealized case, trans-shipment to train gives a lower delivered cost of biomass to a centrally located plant above 100 MW.

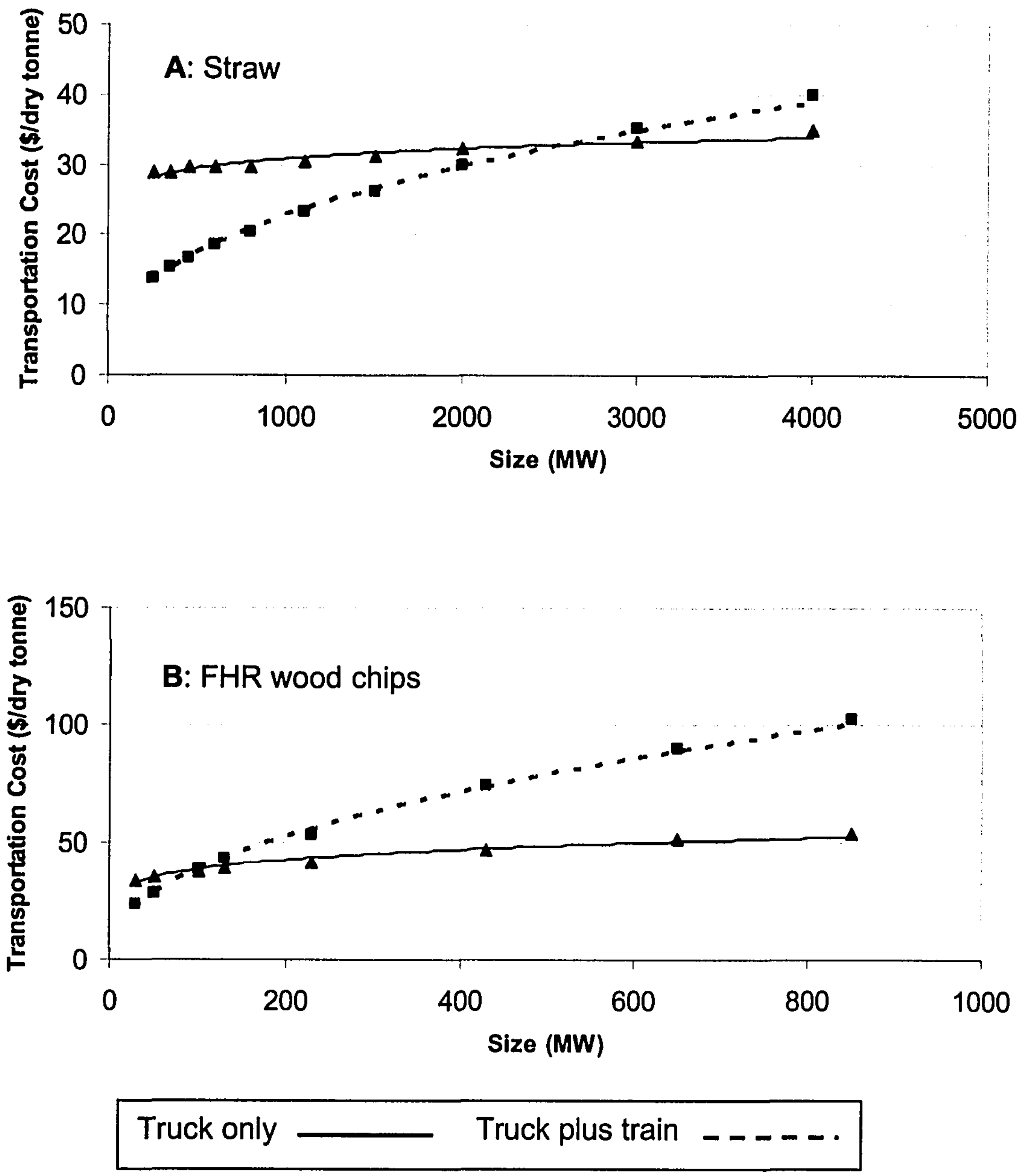

Figure 2-5. Delivered cost of biomass as a function of power plant size.

2.6 Two actual cases in Alberta

The idealized cases assumed that rail lines and sidings were available exactly where needed, and hence from an economic perspective are "best case" analyses. In reality rail lines are well established, and impose their own geographical limitations on plant location. We explore this impact by looking at two specific cases in the Province of Alberta, Canada. Figure 6 shows a map of Alberta, showing existing rail lines. The circles drawn around the S and WC terminals show the area from which we assume that biomass is drawn. The radius is calculated based on the biomass yield and the size of the plant. For the 250 MW straw plant with three terminals the radius of each draw area is 55 km; for the 130 MW wood chip plant with three terminals it is 270 km.

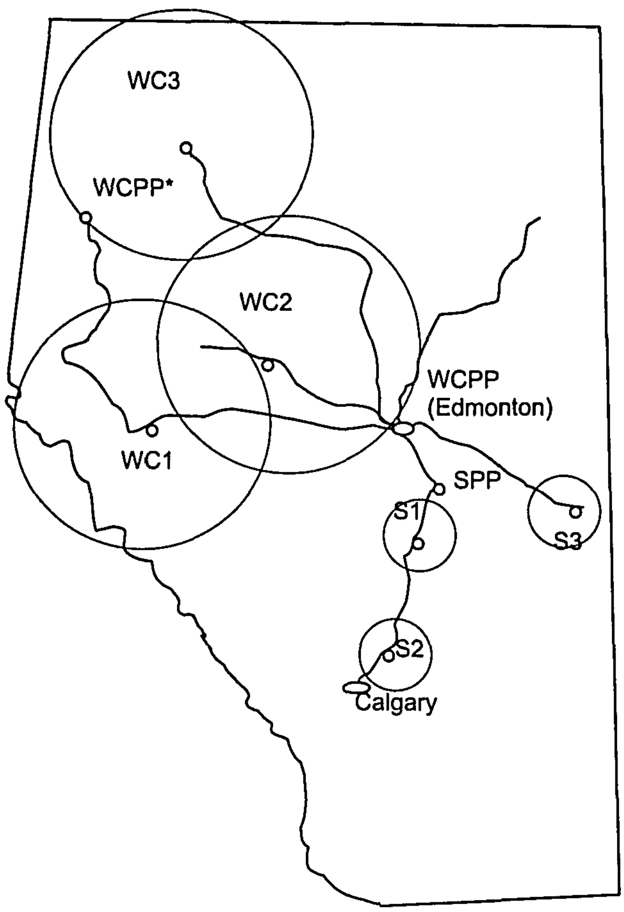

Figure 2- 6. Map of Alberta showing existing rail lines related to two specific prospective biomass power plants.

For the straw case, rail lines in the area of grain growing use Edmonton as a hub. Straw terminals assumed in the specific case are labeled S1 to S3 in Figure 2-6, and the power plant location at Camrose is labeled SPP. Rail haul distances range from 95 to 215 km. Truck haul distances are far higher than in the ideal case because the straw source is not adjacent to the power plant.

For the wood chip case a large draw area uses three rail lines that also converge on Edmonton. In this case, the only practical location for a wood chip power plant supplied by rail is adjacent to the city of Edmonton. Rail distances are high, and range from 160 to 410 km. The terminal locations and power plant location are labeled WC and WCPP in Figure 2-6. Because roads are more prevalent than rail lines in northern Alberta, a wood chip power plant supplied by truck could have a more central location; WCPP* in Figure 2-6 shows the alternate location of a truck supplied wood chip power plant, in Grande Prairie. This is a critical difference between the two transportation alternatives: a more extensive road network allows a more centrally located power plant compared to the restrictions imposed by the layout of the rail system.

Table 2-3 shows the delivered cost of biomass by truck only and truck plus train for the straw and wood chip power plants. Truck only delivery is less expensive than truck plus train for the straw power plant, even though the straw is being drawn from further away than in the ideal case. Truck only delivery is also less expensive than truck plus train for wood chips, because truck transport enables a more centrally located plant. Thus, although in an ideal case trans-shipment of boreal FHR wood chips to train gives a lower cost, the geographic constraints of rail line layout shift the balance in favor of truck transport.

Table 2-3. Cost of biomass transport by truck only and truck plus train for the straw and wood chip power plant ($/tonne)

	Truck only	Truck plus Train
Straw plant in Camrose	25.6	33.7
Wood chip plant in Edmonton (rail) or Grande Prairie (truck)	43.0	44.0

2.7 Discussion

Field sourced biomass, compared to other energy forms, has a low physical and energy density and starts its journey to a processing plant on a truck. For these reasons transportation of biomass is a significant cost, and as biomass processing grows, project developers will place an emphasis on reducing these costs.

Trans-shipment from truck to any other mode of transportation only makes sense if the second mode has a lower cost per km (DVC) than the originating mode. Train transport has a DVC significantly lower than truck transport. However there is a minimum shipping distance required for trans-shipment to be economic, because trans-shipment has incremental fixed costs independent of distance shipped (DFC). Only when the savings in DVC are large enough to offset the incremental DFC is trans-shipment economic.

DVC and DFC are case specific; DVC depends on the transportation mode and the specific location, and DFC depends on the specific biomass being transported. The values for truck transport cited in this study are representative of North America (Kumar et al., 2005) but would not necessarily apply to Europe, for example. DFC reflects the specific equipment and contractual arrangements involved. For example, truck transport in North America is typically through third party carriers who charge for loading and unloading time, while for rail transport in North America it is the shipper, not the carrier, that leases or owns the rail cars and constructs the rail siding and the loading equipment. Thus any analysis of trans-shipment would have to factor in specific values to determine the minimum economic shipping distance.

There is an optimum number of trans-shipment terminals for any two mode transportation scheme. A higher number of terminals increases the fixed costs of trans-shipment, e.g. the investment in land and equipment to move biomass from truck to train, but reduces the truck transport distance and thus reduces the overall DVC incurred. In the ideal analysis we assume that the optimum number of terminals is in place, and calculate MERSD based on that number of terminals. The ideal number of terminals and the biomass moved per terminal depends on the biomass gross yield, i.e. the amount of biomass per total hectares in the draw area. A lower biomass gross yield reduces the value of the optimum amount of biomass moved through each terminal, because truck haul distances increase as biomass yield decreases.

For straw or corn stover in North America we estimate that the MERSD to recover fixed costs of loading dedicated unit trains is 170 km. An economically sized centrally located power plant would have a biomass draw area significantly less than the shipping distances associated with rail trans-shipment; hence using rail would increase, not decrease the overall power cost. For a more diffuse biomass source such as boreal FHR wood chips, we estimate the MERSD to recover fixed costs of loading dedicated unit trains is 145 km. In theory, if rail lines were conveniently located, it would make sense to trans-ship wood chips to rail for transport to an economically sized centrally located power plant.

As this study has shown for one location, the Province of Alberta, Canada, rail lines are usually not ideally located for biomass processing as a fuel or feedstock. Road networks tend to be far more versatile than rail networks for aggregating biomass for processing near the point of origin. In this study, the layout of rail lines would require an Edmonton location for a rail based wood chip power plant, while a truck based power plant could be located more centrally in northwestern Alberta. This difference in location is enough to shift the economics in favor of truck transport. In general, we conclude from this study that the prospects for rail trans-shipment of biomass to centrally located processing plants are limited at best.

Unit trains provide the least expensive form of rail transport for bulk commodities, since the processing of rail cars by the carrier is minimal. If biomass is being shipped in smaller quantities, and especially if it uses rail cars provided by the carrier, charges will be higher, which would increase the MERSD distance.

Long distance shipment of biomass to a non-centrally located processing plant would justify rail transport at distances above the MERSD distance identified in this study. However, economics will likely favor processing close to the biomass source unless the cost of transporting the products of processing biomass, e.g. power or ethanol, are higher than the cost of transporting the biomass itself. Hence, biomass trans-shipment is theoretically economic but in practical terms we expect it to be cost effective only in limited cases where long distance transport is required.

One other possible reason to use rail shipment of biomass even when not economic is to avoid a traffic congestion issue that would otherwise preclude the development of a biomass processing plant. Truck traffic for economically sized biomass power plants could exceed community tolerance; rail shipment by unit train has less impact on communities because rail lines are well established and the additional usage for one or two unit trains per day has a lower impact on people near the transportation corridor.

2.8 Conclusions

The key conclusions from this study are:

- Trans-shipment of biomass from truck to a second mode of transportation will only be economic if the cost per distance traveled is lower for the second transportation mode. It also requires additional fixed costs independent of the distance (DFC), the investment in land and facilities to trans-ship the biomass. Hence there will always be a minimum economic shipping distance for the second transportation mode, since the savings in DVC must offset the incremental DFC.

- For any two mode transportation scheme there is an optimum number of trans-shipment terminals that minimizes overall shipping costs. There is a tradeoff between higher DFC and lower DVC as the number of terminals increases. In this study, 255,000 dry tonnes of straw per year and 100,000 dry tonnes of boreal FHR wood chips are the optimal rates of biomass per terminal.
- Alberta, Canada rail and truck rates are typical of North America. If dedicated unit trains are used for rail transport and the number of terminals is optimized, the MERSD for straw is 170 km, and for boreal FHR wood chips is 145 km.
- A centrally located straw power plant of economic size (250 MW) has a biomass draw area lower than the minimum economic rail distance, and hence trans-shipment to rail will not be economic for such a plant. It might be warranted if community resistance to truck traffic is a major factor in plant sizing.
- A centrally located boreal FHR wood chip power plant of economic size (130 MW) has a biomass draw area larger than the minimum economic rail distance and associated truck travel, and hence trans-shipment to rail would

be economic if rail lines existed that went to a central location.

- The actual layout of rail lines frequently precludes central location of an economically sized biomass processing plant supplied by rail. Road networks frequently allow more flexible location of processing plants than rail lines. In a specific case analyzed in Alberta, the difference in location for a boreal FHR wood chip power plant tips the balance in favor of truck transport.

2.9 Acknowledgements

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Chapter 3

Life Cycle Analysis of Biomass Transportation: Trains vs. Trucks*

3.1 Overview

Biomass for energy conversion is regarded as a key renewable resource in future energy systems. Basically, biomass stores solar energy and it can be used to generate electricity or upgraded to solid or liquid fuels. Limitations on the import of fossil fuels and the need to abate carbon emissions from fossil fuels both create an incentive to commercialize biomass utilization (Borjesson, 1999).

Bioenergy is often regarded as a highly localized resource, and many development schemes have been based on small scale processing. However, many studies of biomass projects have probed the tradeoff between rising transportation costs and higher capital efficiency as project size increases. Such studies generally find that larger projects which draw biomass from a greater area are more economic (Kumar et al., 2003; Jenkins, 1998; Dornburg and Faaij, 2001). With appropriate logistic systems, biomass can be economically accessed over a large geographical area (Forsberg, 2000). However, the logistic systems are a key component in overall project decision making (Overend, 1982). Biomass resources have an energy density that is significantly less than coal or oil. As a result, transportation is a major cost factor. In one study transporting biomass 40 km contributed 25% of the delivered cost of the fuel

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* A version of this chapter has been published. Mahmudi et al., 2005. SAE World Congress, Detroit, USA.

(Borjesson and Gustavsson, 1996). This contrasts with fossil fuel plants, where transportation cost is often a minor cost. Examples include power plants built at the coal mine or power plants using fossil fuels delivered by pipeline or ship.

This study focuses on transportation of two forms of biomass that are abundant in western Canada: wood and agricultural residues such as wheat and barley straw. The boreal forests in Canada are already committed to forestry projects, and hence in this study we focus on forest harvest residues, the limbs and tops of trees that are harvested for pulp or lumber. (Note that mill wastes, such as sawdust and bark, are not included in this study because to a large extent they are already being utilized in energy projects.) The boreal forest has a harvest rotation of approximately 100 years. About 20% of the standing biomass in trees is stripped during delimbing and topping, and is left at the side of logging roads. In current forestry practice this material is burned to reduce the threat of forest fires; hence recovery of this material and use in an energy project is an ideal biomass project. Density of forest harvest residues is estimated at 0.247 dry tonnes/gross ha, where gross ha includes both forests and land not used for forestry, such as access roads and communities (Kumar et al., 2003). Similarly, a large portion of wheat and barley straw is currently left on the field after grain harvest, where it rots. Previous studies have shown that annual recovery of straw does not decrease soil carbon for black soils (Hartman, 1999) and hence as with forest harvest residues, recovery of straw in black soil areas is an ideal biomass project. Straw density is estimated at 0.416 dry tonnes/gross ha (Kumar et al., 2003). These biomass yields, which are typical for Canada, are used to determine draw areas and transportation distances for this study. Regions with higher biomass productivity would have smaller draw areas and slightly different economic plant sizes. The emission factors for transport are determined per tonne km and can be generalized to other locations.

In this study biomass is delivered to two projects: a 250 MW straw based power plant with a draw area of 28,500 km^2 (equivalent to a radius of 95 km), and a 130 MW forest harvest residues plant with a draw area of 735,000 km^2 (equivalent to a radius of 490 km). Plant sizes are based on an earlier study of power cost vs. plant size; the 130 MW plant is at optimum size, and the 250 MW plant is below the optimum size of 450 MW but at a size where the cost of power is negligibly higher than at optimum (Kumar et al., 2003). Power generation is one of many ways that biomass can be utilized; a recent study by the United States National Energy Renewable Laboratory (NREL) emphasized the role that biomass power could play in the generation mix in the US, with positive environmental impact. Energy usage and emissions during biomass transport are not significant in comparison to the benefit of substituting biomass for coal in the power plant (Kaltschmitt et al., 1997).

All land biomass starts its journey from field to plant on a truck. For ongoing transport to a biomass processing plant, three transportation options are available. These include continued use of trucks all the way to the processing plant or unloading at a terminal for further transport by either train or pipeline. Previous studies have shown that pipeline transport is not suited for combustion applications, due to uptake of the carrier fluid by the biomass (Kumar et al., 2004). If the carrier fluid is water the uptake reduces the lower heating value of the biomass to such an extent that the requirement for additional biomass overwhelms any cost savings from pipeline transport. Straw reaches a moisture level of 80% and effectively has no LHV, and the moisture level of wood increases from 45% to 65 to 67%, dropping its LHV drops by 78%. (Note that pipeline delivery of biomass in a water-based carrier to aqueous processes, such as alcohol fermentation plants, would not suffer from the energy penalty discussed above.) Conversely, if the carrier fluid is oil, the uptake of oil is at least 30% by mass, and the delivered fuel, on an energy basis, is 2/3 oil and 1/3 biomass, significantly diluting the greenhouse gas abatement from using biomass and increasing the net cost of the fuel (Kumar et al., 2004). Hence, in this study we eliminate pipelining as a transportation mode and analyze truck vs. truck-plus-train.

In this chapter we use a LCA-based information on emissions from the two biomass transportation modes, and briefly discuss technical issues for each mode and previous economic studies of transportation cost.

3.2 Use of published LCA data

Life cycle assessment studies are a management tool developed to analyze a product/activity from an environmental point of view (Kaltschmitt et al., 1997). A product has certain impacts during its life cycle from "cradle to grave"; LCA focuses on the total impact of a product through every step of its life. The goal of this study is to evaluate the environmental load of land based modes of transportation of biomass to combustion based plants based on the results of published LCA studies. This required development of a functional unit, process flow map, boundary selection and stressor categories in order to interpret the result of existing LCA studies. To adapt the results of other studies to a common basis, the functional unit for this study is the transportation of one tonne of biomass a distance of one km. Figure 3-1 shows the process flow map and system boundary for truck only and truck-plus-train transport.

The boundary is selected to focus on only the difference in transportation mode. Note that the process flow map is based on logging and agricultural practices in western Canada. Trees are cut and skidded to the roadside before delimbing and topping, so that forest harvest residues start as a strip of material at the side of a logging road; straw is baled on a second pass over a field after the first pass of the combine recovers the grain. No new roads or rail lines are being built, so stressors do not include any land disturbance, and are limited to air emissions, both those with a long range impact (greenhouse gases, e.g. CO_2), and those with a short range impact on local air quality, including acid rain precursors

(ARP) such as NO_x, SO_2 and volatile organic compounds (VOC) such as HC and also CO.

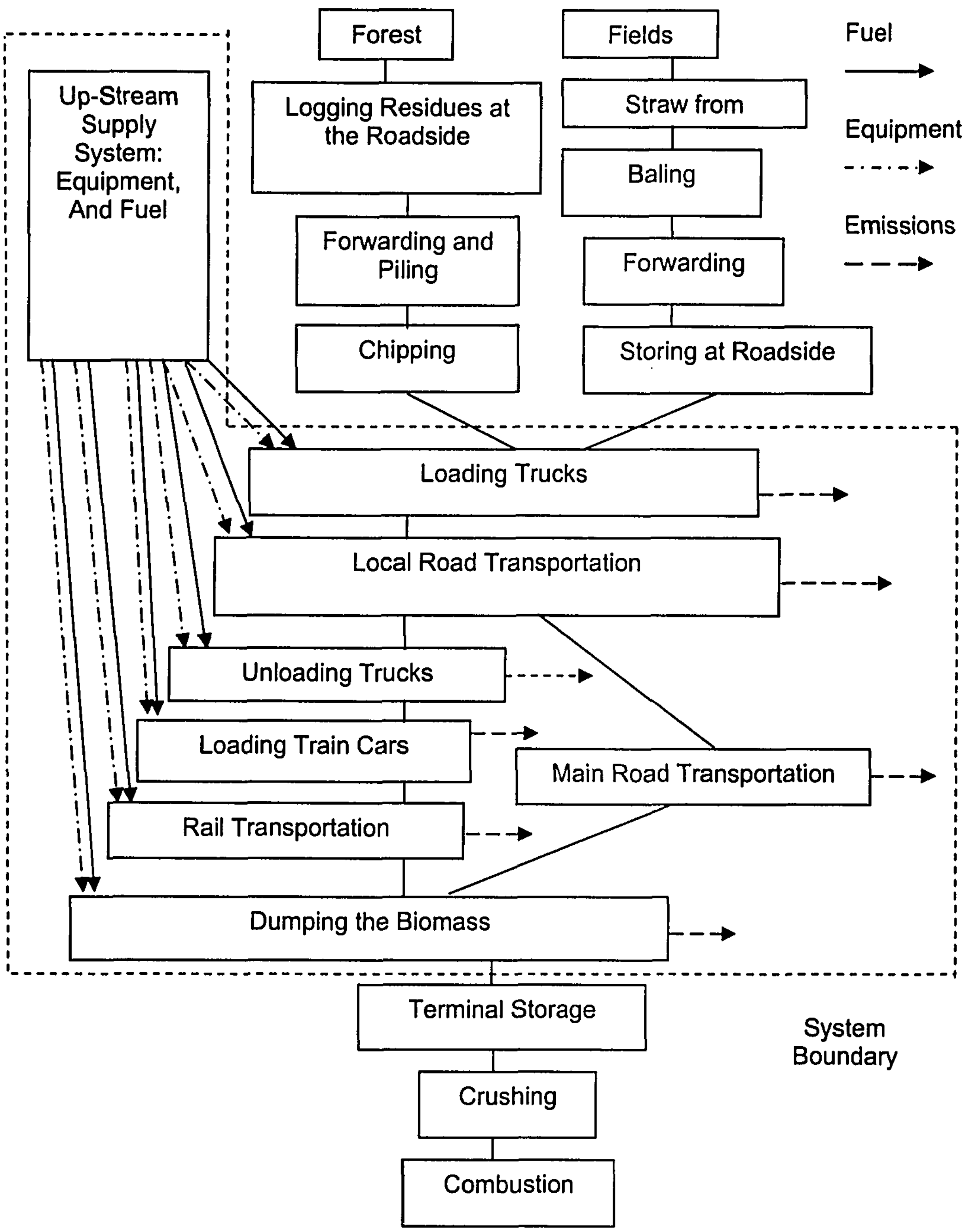

Figure 3-1. LCA Process Flow Map and the System Boundary

3.2 Inventory of data

Three published studies provided the primary LCA information:

- A Railway Association of Canada (RAC) study (The Railway Association of Canada, 2002) compares truck and train emissions in g per tonne km based on full LCA inputs that include manufacturing and disposal of equipment and emissions arising from manufacturing of the fuel.
- A comparable study by Borjessen et al. also for truck and train, but based on data from European truck and train equipment. Borjessen et al. draw on a wide variety of sources in their study (Borjesson and Gustavsson, 1996).
- A study by the Swedish Network for Transport and Environment (NTM) for trains only (Nätverket för Transporter och Miljön, 2004).

The third source (NTM) also provides information for trucks but the truck information is based on direct truck use only, not including upstream emissions. The NTM truck information (Nätverket för Transporter och Miljön, 2004) is very similar to another truck study by Forsberg (Forsberg, 2000). These two sources differ significantly from the results of RAC and Borjessen et al. because they do not include upstream supply emissions associated with equipment and fuel manufacturing and disposal. The study by Forsberg determined emissions per kWh for a plant with an average transportation distance of 50 km (Forsberg, 2000). These emission data were converted to the functional unit of this study. The study of trucks by NTM (Nätverket för Transporter och Miljön, 2004) determined emissions per g per l of fuel used; again these data were converted to the functional unit of this study based on an average fuel usage or 30 l per 100 km for a fully loaded truck haul and empty return.

Table 1 shows a consolidated set of emission data from all sources for truck and train emissions. The NTM study of truck emissions tracks reductions for truck diesel engines over the period 1980 to 2000; the data reported in Table 3-1 are for a 2000 Scania diesel. The significant difference between full LCA truck emissions that include upstream contributions and the emissions from truck transportation only illustrates the need for finding a common basis to evaluate transportation modes, and emphasizes the impact of upstream factors in total LCA assessment of environmental impact.

Rail transport requires that biomass be unloaded from a truck and reloaded on a rail car, steps that would most likely be performed by equipment such as a specialized front end loader. Emissions from these steps would reduce the gap between truck and train transport. Forsberg calculated emissions not only for transportation but also for other steps in the delivery of biomass; these, converted to this study's functional unit, are shown in Table 3-2 (Forsberg, 2000). From inspection it is evident that emission factors for loading or unloading steps are very low compared to those for transportation (less than 1%), and can be ignored in comparing emissions from truck vs. train transport.

Table 3-1. Environmental emissions: truck vs. train (g/km.tonne)

	Truck: Excluding upstream		Truck: Full LCA[a]		Train: Full LCA[a]		
Source Stressor	Forsberg[b]	NTM[c,d]	RAC[e]	Borjesson[f]	RAC[e]	Borjesson[f]	NTM[c,d]
CO_2	41.3	20.52	75.5	72.6	21.8	38.5	18
CO	0.124	0.165	0.747	0.36	0.063	0.07	0.049
NO_x	0.38	0.126	1.58	1.10	0.329	0.36	0.36
SO_2	0.014	N/A	0.027	N/A	0.015	N/A	0.014
HC	0.126	0.10	0.105	0.09	0.017	0.014	0.023

a - The numbers are for whole life cycle including the upstream supply system such as equipment and fuel. b - The data were converted from kg/MWh to g/tonne km based on the thermal efficiency and driving distances cited by Forsberg (Forsberg, 2000). c - The data were converted from g/l to g/tonne km using factors presented by NTM (Nätverket för Transporter och Miljön, 2004). Calculations are based on a 26 ton payload hauled one way by a heavy lorry with trailer, returning empty; average fuel consumption is 30 l/100 km. d - Based on a Scania 2000 engine. e – (The Railway Association of Canada, 2002). f – (Borjesson, 1996; Borjesson and Gustavsson, 1996)

Table 3-2. Environmental emissions for trucks during different steps of transportation (g/km.tonne)[a,b]

Units	CO_2	CO	NO_x	HC	SO_2
Forwarding biomass	133.0	0.734	2.71	0.181	0.218
Storing	-	-	-	-	-
Bailing of biomass	167.4	0.894	3.37	0.225	0.271
Loading trucks	0.2	0.002	0.02	0.001	0.001
Truck transportation	41.3	0.124	0.38	0.014	0.126
Dumping biomass	0.2	0.002	0.02	0.001	0.001
Terminal storage	-	-	-	-	-
Total	342.1	1.755	6.50	0.421	0.616

a - The data were converted from kg/MWh to g/tonne km based on the thermal efficiency and driving distances cited by Forsberg (Forsberg, 2000). b - Missing numbers were reported by Forsberg to be so small as to be negligible (Forsberg, 2000).

3.4 Discussion

3.4.1 Life cycle comparison of truck and rail transport

Biomass transport always involves trucking as an initial step, since it is diffuse in origin and most often only accessed by rural or logging roads. Hence, for the initial portion of its journey from field to plant trucking is the only practical transportation mode. However, biomass going to a combustion based plant can be transferred to train at a rail head. Both the Canadian and European data based on full LCA emissions support the conclusion that for the remaining travel distance, emissions are substantially reduced by train transport. Table 3-3 shows the percentage reduction in stressors for the two data sets for which full LCA emissions are available for both truck and train.

Table 3-3. Impact assessment for different methods of transportation

	Reduction in emissions: Train vs. Truck, %	
Stressors	RAC [a]	Borjesson [b]
CO_2	71	47
CO	91	78
NO_x	79	67
HC	83	97
SO_2	44	N/A

a – (The Rail Association of Canada, 2002). b – Borjesson, 1996; Borjesson and Gustavsson, 1996)

Data on emissions during train transport are very similar for all stressors except CO_2; the difference in this stressor may arise from the size of train assumed in the studies as well as engine efficiency; note that one data set from a European source is very close to a data set from a Canadian source; a third data set from Europe is different. Data on emissions during truck transport are similar for all stressors except CO; the cause of this difference is not known

One advantage of rail is simple physics: steel wheels on steel track produces noticeably lower friction than rubber tires on pavement. Trains also have a longer life than trucks; 30 years is a typical life for a train engine (Stenvold, 2004), while a more typical figure for a truck tractor is 15 years. In addition, train loads are far higher than truck, allowing a larger and more efficient engine. Finally, the rail system has lower grades than roads, and less required stops; locomotives and cars can be coupled together to gain maximum rolling efficiency, and there are fewer and less severe periods of acceleration and deceleration for train than truck. Because of the first and last factors (low rolling resistance and moderate grades), much less horsepower is needed to move goods on rail.

For instance, less than 100 Hp is required to transport a truckload equivalent of materials on rail. This compares to 400-500 Hp in the average heavy-duty diesel truck (The Rail Association of Canada, 2002). Similarly, energy intensity is lower for train transport; Borjessen reported an energy intensity for trains of 0.68 MJ/tonne km, vs. 1.3 for truck (Borjesson, 1996). A Canadian study cites comparable reduction in train and truck energy intensity over the time period 1990 to 1999, with the reduction in train emissions coming in part from to larger trains and more efficient track sharing between carriers (The Rail Association of Canada, 2002). For all of these reasons trains have significantly lower emissions of all stressors than trucks over a full life cycle.

Looking into the future at the potential for improvement, one can forecast an emphasis on improving energy intensity and reducing emissions in both truck and train transportation. Given that over the last 10 years the reduction in energy intensity has been comparable between the two modes, as noted above, and given the large gap in emissions between the two modes, we see little likelihood that the conclusion of this work will change, namely that using a combination of trucks and train to deliver biomass to large projects leads to substantially lower emissions of stressors as compared to the use of trucks only.

3.4.2 Other technical and economic comparisons of truck versus rail

Both truck and train are viable and well developed transportation alternatives which carry a significant bulk freight capacity. A Canadian study (The Rail Association of Canada, 2002) noted that 60% of the total volume of land freight shipments in Canada are by rail with the balance by truck.

In addition to emission considerations, two other factors suggest train vs. truck delivery of biomass: road congestion and cost of delivery. Power generation, whether from fossil fuel or biomass, is not economic at small plant sizes; the reduction in capital cost per unit output is larger than the incremental increase in fuel transportation cost up to large power plant sizes: 130 MW for forest harvest residues, and up to 450 MW for straw (Kumar et al., 2003). Table 3-4 shows the critical technical parameters for these sizes of power plant, for two cases: delivery of all fuel to the power plant by truck, and delivery of fuel by truck to three train terminals, which then forward the fuel to the power plant in 100 car unit trains. Note that in the case of a 250 MW straw power plant, delivery of straw in 16.8 tonne truckloads (a full load for a typical flatbed truck specialized for hauling large round bales) would require a truck to arrive at the plant every 6 minutes on average, 24 hours per day. This intense delivery schedule would require special consideration in locating the power plant: it would need to be near a major road, with access that avoided local communities. This contrasts to delivery of the straw by unit train, in which case less than 2 trains are required per day, (three terminals per plant times 0.48 trains per terminal = 1.44 trains per day). This level is less likely to arouse community resistance.

Studies of a full cost analysis of truck only vs. truck-plus-train delivery of biomass are limited. Borjesson did a study in a European context that suggests that rail is favored over truck for total transport distances in excess of 100 km, and if available transfer to ships is favored for total transport distances in excess of 450 km (Borjesson and Gustavsson, 1996). More detailed studies of the cost of transfer to train in both North American and European settings would add to the evaluation of truck vs. train transport. While this study is focused on biomass for energy, similar conclusions would result from studying other bulky commodities which are broadly distributed and must be delivered to a single destination.

Table 3-4. Technical Calculations for Truck vs. Train Transportation

Fuel Type	Straw	Wood chips
Power plant size (MW)	250	130
Fuel moisture level (%)	16%	45%
Fuel HHV (MJ/kg)	18.3	20.3
Fuel LHV (MJ/kg)	14.04	9.36

Plant efficiency	34%	34%
Operating factor	0.85	0.85
Biomass demand (dry Mtonnes/year)	1.179	0.602
Biomass demand (Green) (Mtonnes/year)	1.404	1.094
Train size (cars)	100	100
Train capacity (cubic meters/car)	190	190
Fuel density (kg/cubic meters)	140	290
Train capacity (tonnes/car)	26.6	55.1
# of trains for a terminal (per day)	0.48	0.18
Truck capacity (tonnes/truck)	16.8	34.8
# of trucks for the power plant (per day)	229	87
<u>If delivery by truck-plus-train:</u>		
# of terminals	3	3
Biomass demand/terminal (Mtonnes/year)	0.468	0.365
# of trucks per terminal (per day)	76.3	28.74
Trucks arrival time: Terminal (Min)	19	50
<u>If delivery by truck only:</u>		
Trucks arrival time: power plant (Min)	6	16

3.5 Conclusions

A study based on life cycle assessment results confirms that trans-shipment of biomass from truck to train has a significant environmental advantage. GHG emissions drop by well over half and other emissions related to acid rain and urban pollution drop by an even higher margin. In addition, trans-shipment of biomass from truck to train provides a means to limit the impact of road congestion and community resistance at biomass projects large enough for economic viability. Data on the cost of trans-shipment of biomass from truck to train are more limited, and a total assessment of biomass transportation mode would be helped significantly by more data in this area.

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Chapter 4

Conclusions and future research

4.1 Conclusions

Trans-shipment of biomass from truck to a second mode of transportation is only economic when the DVC is lower for the second mode. Furthermore any kind of trans-shipment needs an additional DFC for the extra facilities and equipment at the switching points. Therefore the lower DVC should offset the incremental DFC; this requires a minimum economic shipping distance for the second mode.

To minimize the overall shipping costs an optimum number of trans-shipment switching points may be calculated. This optimum is based on the tradeoff that exists among the number of terminals (increasing the number of terminals cause higher DFC and lower DVC, by shortening the distance biomass is carried by truck). In this research 255,000 dry tones of straw per year and 100,000 dry tones of FHR wood chips are the optimal rates of biomass per terminal. In the case of Alberta, Canada for rail trans-shipment at the optimum number of terminals, the MERSD for straw is 170 km, and for boreal FHR wood chips is 145 km.

In the case of a centrally located 250 MW straw fire plant the biomass draw distance is lower than the minimum economic rail distance. Therefore, trans-shipment to rail will not be economic.

A centrally located boreal FHR wood chip power plant of economic size (130 MW) draws biomass from an area larger than the minimum economic rail distance and associated truck travel. Thus in theory trans-shipment to rail would be economic if existing rail lines ran to a central location. The actual layout of rail lines frequently precludes central location of an economically sized biomass processing plant supplied by rail, while road networks frequently allow more flexible location of processing plants than rail lines. In a specific case analyzed in Alberta, use of roads allows a different location for a boreal FHR wood chip power plant, and this tips the balance in favor of truck transport.

A study based on consolidated life cycle analysis results confirms that trans-shipment of biomass from truck to train has a significant environmental advantage. GHG emissions drop by well over half and other emissions related to acid rain and urban pollution drop by an even higher margin.

The cost model which has been developed and used in this study is a deterministic model and like all models from this type, the end results are dependant to the assumed values used as the input variables. Deterministic models can be combined with sensitivity studies to identify the impact of particular variable on outcomes. This was not done in this study, but is a possible area of future research. Models that incorporate probabilistic distributions of key variables, such as Monte Carlo simulation, are possible in theory but in practice data on the correct distribution of the probability of input parameters is not available.

4.2 Recommendations for future research

This study shows little economic promise for rail trans-shipment of biomass to power plants, despite the lower environmental load from rail vs. truck transport.

Whether rail transport is economic depends on the scale of the facility to which biomass is being delivered. Optimum sized power plants are in the range of 130 to 450 MW, but there is currently growing interest in the concept of an integrated biorefinery that would produce fuel ethanol, specialty chemical, and power. It is likely that an economic sized biorefinery would be significantly larger than an economic sized biomass based power plant, because of the higher capital investment required for the biorefinery due to its multiple processing steps. This would also aggravate road congestion issues. Hence the conclusions of this study should be considered to be specific to power generation from biomass in a North American context, and the potential for trans-shipment to rail would need to be reevaluated for a bio-refinery. Note, however, that pipeline transport of biomass to a biorefinery is also an option since the first stage of processing in such a plant is aqueous; hence a further study would be to compare rail vs. pipeline trans-shipment of field sourced biomass to a large biorefinery processing complex.

Critical parameters in trans-shipment depend on the relative costs of truck vs. rail transport. These, in turn, could be specific to a regional location. For instance, in North America 20 tonne and 40 tonne tandem truck loads are common and readily accommodated on most highways, whereas in other settings such large trucks are precluded by the road system. In addition, transport costs vary by region. Thus for other locations, for instance China or Europe, the minimum economic rail shipping distance may be different than those calculated in this study for a North American setting.

This study also points out the impact of the location of rail lines to the economics of a plant supplied by rail; rail lines were developed for prior needs, e.g. grain transport or resource extraction, and often radiate from large urban centers. In the case of rail transport of wood chips over rail in Alberta the existing routing of rail lines requires an Edmonton based location for a rail supplied wood chip power plant, whereas a truck supplied plant could be more favorably located in Grande Prairie. This study did not explore whether it would ever be economic to construct new rail lines, either wholly dedicated lines or cross links between the existing lines in Northern Alberta that would better enable a more central location of a power plant. While the construction of new rail lines in boreal forests is likely uneconomic, there could possibly be specialized circumstances in which short lines could be justified.

As noted above, one area of future research would be a systematic evaluation of the sensitivity of the results of this deterministic model to changes in key input parameters. Since transportation cost elements such as labor, fuel, and capital are subject to change, understanding of key sensitivities would help identify likely changes in overall transportation cost for various future scenarios.

Appendix A

This appendix illustrates the methodology to determine critical transportation parameters for rail trans-shipment of biomass.

Figure A-1 shows a schematic diagram illustrating the interaction of technical transportation parameters such as truck arrival time or number of trains per day for straw; a similar set of relationships were developed for wood chips. The starting parameter is the power plant capacity, which in turn can be related to biomass demand through the parameters of power plant efficiency and biomass energy content. By specifiying the capacity of truck and train and the number of trans-shipment terminals, the biomass demand relates to the number of trains per day and the truck arrival frequency.

Figure A-2 is a schematic diagram showing the interrelationships that determine the size of forklift fleet required at each straw trans-shipment terminal. Note that wood chips are deposited over a dump pocket, and hence a fleet of forklifts is not required. We assumed that each wood chip trans-shipment point would have a small bulldozer and a front end loader.

Table A-1 shows sample values of transportation parameters derived from a model in Excel based on the interrelationships shown in Figure A-1 and A-2. The model allowed alternate parameters to be entered for the analysis of different cases.

Table A-2 shows sample values of a model to determine the area from which biomass must be drawn to support the power plant; critical inputs include biomass gross yield, i.e. the amount of biomass available per gross area, where gross area includes all land in the region, including roads, communities, industry and any other non-farming or non-forestry use.

Figure A-1. Number of trucks vs. trains analysis based on biomass demand

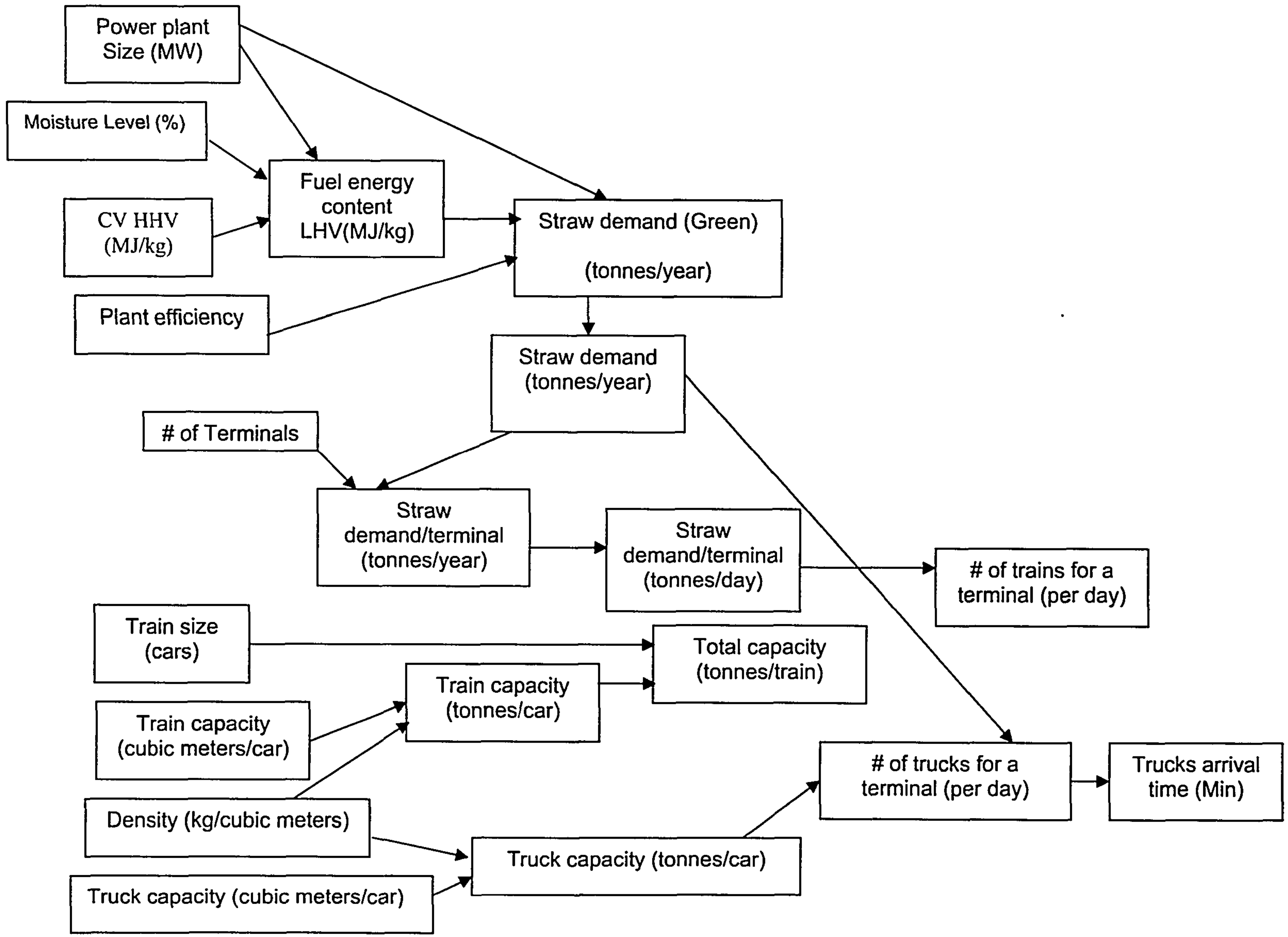


Figure A-2. Number of forklifts per terminal

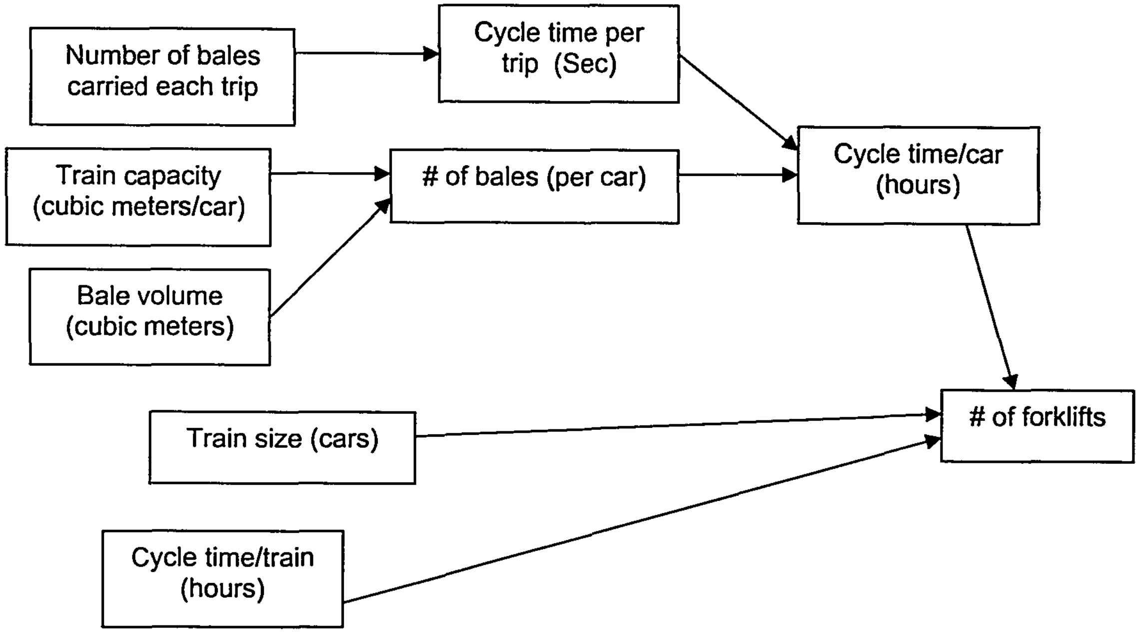


Table A-1.Some technical parameters used to build the cost model

Fuel Type	Straw	Forest Residues
Optimum power plant size (MW)	250	130
Moisture level (%)	16%	45%
CV HHV(MJ/kg)	18.3	20.3
Fuel efficiency LHV(MJ/kg)	14.04	9.36
Plant efficiency	34%	34%
Biomass demand (Green Mtonnes/year)	1.404	1.095
Biomass demand (dry Mtonnes/year)	1.179	0.602
# of Terminals	3	3
Biomass demand/terminal (Mtonnes/year)	0.468	0.365
Biomass demand/terminal (tonnes/day)	3,846	3,000
Biomass demand/terminal (tonnes/day)	1,282	1,000
Train size (# of cars)	100	100
Train capacity (cubic meters/car)	190	190
Density (kg/cubic meters)	140	290
Train capacity (tonnes/car)	26.6	55.1
Total capacity (tonnes/train)	2660	5510
# of trains for a terminal (per week)	3.37	1.27
# of trains for a terminal (per day)	0.48	0.18
Truck capacity (cubic meters/car)	120	120
Truck capacity (tonnes/car)	16.8	34.8
# of trucks for a terminal (per week)	534.2	201.1
# of trucks for a terminal (per day)	76.3	28.74
Trucks arrival time (Min)	18.87	50.11
Number of bales carried each trip	2	-
Cycle time per trip (R.bales) (sec)	120	-
Cycle time/car (hours)	1.66	-
Cycle time/train (hours)	9	-
# of Forklifts required	18	
Cycle time per trip (S.bales) (sec)	120	-
Cycle time/car (Hours)	1.56	-
Cycle time/train (Hours)	9	-
# of Forklifts required	17	-

Table A-2. Calculations on the draw distance for economically sized centrally located power plants.

Technical Parameters	Straw	Wood chips
Hours per day	24	24
Days per year	365	365
Operating factor	0.85	0.85
MW	250	130
MJ per MWh	3600	3600
Efficiency, LHV	0.34	0.34
Chemical hydrogen content of biomass, mass % (wet basis)	4.8%	3.9%
Moisture level, %	16.0%	45.0%
Heating content, HHV, MJ per kg	18.3	20.3
Heating content, LHV, MJ per wet kg	14.04	9.36
Wet tonnes per wet kg	0.001	0.001
Dry tonne per wet tonne	0.84	0.55
Dry tonnes per ha	0.416	0.247
Years of cutting	1	30
Biomass demand, green tonnes per year	1,403,787	1,094,997
Biomass demand, dry tonnes per year	1,179,181	602,248
Hectares required per year	2,834,570	2,438,252
Hectares required over life of project	2,834,570	73,147,551
km^2 over life of project	28,346	731,476
Radius of circle	95.0	482.5
Average driving distance	67.2	341.2

Appendix B

A critical part of this study is an estimation of the costs of trans-shipment of biomass. In this Appendix key cost parameters are illustrated.. The model is based on North American rail industry's figures (Johnson, 2004; Kumar et al., 2004; Laver, 2004; Nicholson, 2004; O'Brian, 2004; Simmons, 2004; Stenvold, 2004). Specific calculations for the development of geographically specific cases (a 250 MW straw fired power plant in Camrose, Alberta and a 130 MW wood chip fired power plant in Edmonton, Alberta) are based on three trans-shipment terminals.

Table B-1 shows sample values for the cost factors in trans-shipment of straw. One element of Table B-1 is labor cost, and the value in Table B-1 is drawn from a detailed model of labor costs illustrated in Table B-2.

Table B-3 shows sample values for the cost factors in trans-shipment of wood chips. As with the case of straw, one element in Table B-3 is labor cost, and the value in Table B-3 is drawn from a detailed model of labor costs illustrated in Table B-4.

Table B-1. The cost model for a 250 MW straw plant

# of terminals	3
Capital cost	
Purchase of cars	
Per car	$ 95,000
Per train	$ 9,500,000
Total	$ 28,500,000
Purchase of forklifts	
Per forklift	$ 22,000
Per terminal	$ 418,000
Total	$ 1,672,000
Trailer buildings	
Per trailer	$ 15,000
# of trailers	6
Total	$ 90,000
Total	$ 30,262,000
i	10%
Capital Recovery Factor (CRF)	$ 3,210,170
Opertating cost	
Direct operating cost	
Wages (from Table B-2)	$ 3,966,000
Rent for usage of facilities at terminals (Including land for storage)	
per terminal	$ 150,000
Total	$ 450,000
Total	$ 4,416,000
Maintenance cost	
Maintenance cost for forklifts (2% of capital per year)	$ 33,440
Maintenance cost for cars (1% of capital per year)	$ 285,000
Total	$ 318,440
Total	$ 7,944,610
Cost per dry tonne	$ 6.74

Table B-2. Labor cost estimation for the 250 MW straw plant

# of terminals			3
Wages			
	Operators		
	Forklift drivers		
		per driver	$ 40,000
		# of drivers	54
		Total	$ 2,160,000
	Permanent operators		
		Operators working on the weigh scale	
		per operator	$ 40,000
		# of operators (assuming 4 shifts)	16
		Total	$ 640,000
		Foremen	
		per foreman	$ 60,000
		# of foremen	4
		Total	$ 240,000
		Maintenance staff	
		per operator	$ 50,000
		# of operators	2
		Total	$ 100,000
	Administrative staff		
		Clerical staff (located at the plant)	
		per staff	$ 30,000
		# of staff	3
		Total	$ 90,000
		Transportation manager	$ 75,000
20% for staff benefits			$ 661,000
TOTAL			$ 3,966,000

Table B-3. The cost model for a 130 MW wood chip plant

# of terminals	3
Capital cost	
Purchase of cars	
per car	$ 80,000
per train	$ 8,000,000
Total	$16,000,000
Purchase of front loader	
per front loader	$ 30,000
# of front loaders	4
Total	$ 120,000
Purchase of bulldozer	
per bulldozer	$ 100,000
# of bulldozers	4
Total	$ 400,000
Purchase of land for storage	
per hectare	$ 1,000
per terminal	$ 3,000
Legal and Admin.	$ 20,000
Total	$ 32,000
Building tracks at terminals	
per km	$ 300,000
per terminal	$ 1,200,000
Total	$ 4,800,000
Trailer buildings	
per trailer	$ 15,000
# of trailers	3
Total	$ 45,000
Mechanisms	$ 450,000
(Including conveyor belt, dumping system and dump pocket)	$ 1,350,000
Total	$ 22,747,000
i	10%
Capital Recovery Factor (CRF)	$ 2,412,985
Operating Cost	
Direct operating cost	
Wages (from Table B-4)	$ 1,242,000

Total	$ 1,242,000
Maintenance cost	
Maintenance cost for heavy machines (2% of capital per year)	$ 10,400
Maintenance cost for cars (1% of capital per year)	$ 160,000
Total	$ 170,400
Total	$ 3,825,385
Cost per dry tonne	$ 6.35

Table B-4. Labor cost estimation for the 130 MW wood chip plant

# of terminals			3
Wages			
	Permanent operators		
		Bulldozer drivers	
		per driver	$ 40,000
		# of drivers	4
		Total	$ 160,000
		Fornt loader drivers	
		per driver	$ 40,000
		# of drivers	4
		Total	$ 160,000
		Foreman (also operator) on the weigh scale	
		per operator	$ 60,000
		# of operators (assuming 2 shifts)	8
		Total	$ 480,000
		Maintenance staff	
		per operator	$ 50,000
		# of operators	2
		Total	$ 100,000
	Administrative staffs		
		Clerical staff (Located at the plant)	
		per staff	$ 30,000
		# of staff	2
		Total	$ 60,000
		Transportation manager	$ 75,000
20% for staff benefits			$ 207,000
TOTAL			$ 1,242,000

Appendix C

Determination of the minimum economic rail shipment distance (MERSD) at which the savings in DVC offsets the incremental DFC of trans-shipment was based on an idealized case for each of straw and wood chips. In the idealized case the number of trans-shipment terminals is optimized to give the lowest overall net transportation cost.

An optimum in the number of trans-shipment terminals exists because of a tradeoff between higher fixed costs vs. shorter truck hauling distances and longer train hauling distances as the number of trans-shipment terminals increases. Since rail shipping is less expensive than truck, the shorter truck hauls offset the increased investment in trans-shipment terminals.

This Appendix illustrates the model for determining the distance at which the savings from rail DVC exactly offset the incremental DFC from trans-shipment; at this point the cost of trans-shipment of biomass to rail exactly equals the cost of shipment by truck only. The minimum total shipping distance at which trans-shipment cost equals trucking cost is associated with the optimum number of trans-shipment terminals; in effect the minimum distance is equivalent to the minimum cost achievable by the combination of truck plus rail shipment. The calculation approach is iterative: distance at which of shipment is calculated for an increasing number of trans-shipment terminals.

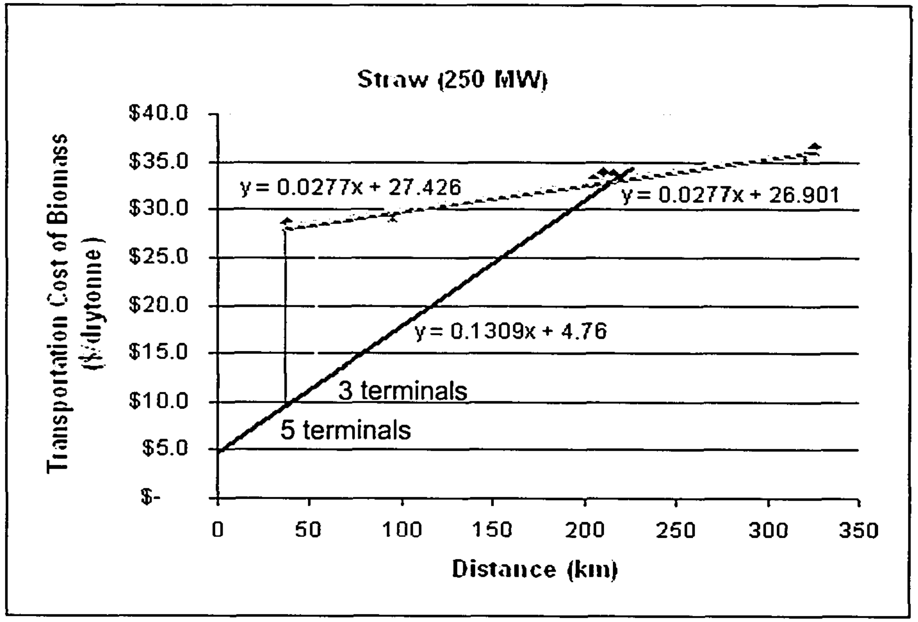
Spreadsheet C-1 illustrates for the case of supplying straw to a 250 MW power plant the calculation of the distance at which rail trans-shipment equals trucking costs, the intersection of the two lines of transportation cost in the plot included in the spreadsheet. Table C-1 and Figure C-1 show that the minimum distance, equivalent to the minimum cost, occurs at 5 terminals, which would each process 255,000 dry tonnes per year.

Spreadsheet C-2 shows the corresponding work for the case of supplying wood chips to a 130 MW power plant. Table C-2 and Figure C-2 show that the minimum distance occurs at 6 terminals, which would each process 100,000 dry tonnes per year.

Spreadsheet C-1. Calculations for finding the optimum number of trans-shipment terminals (250 MW straw plant).

DVC calculations (Rail)
Cost vs. Distance (Straw)

	Dist. (km)	CDN ($)	CDN ($)	CDN ($)
	95	$ 19.1	$ 29.5	$ 29.0
	215	$ 23.2	$ 33.6	$ 33.1
	38	$ 18.2	$ 28.6	$ 28.1
	205	$ 22.7	$ 33.1	$ 32.6
	320	$ 25.4	$ 35.8	$ 35.2
	210	$ 23.4	$ 33.8	$ 33.3
	325	$ 26.2	$ 36.6	$ 36.1
6.737395				
54.85525				CDN ($)
54	11.8286			$ 29.2
54	28.945712			$ 33.3
DVC calculations (Truck)				$ 28.3
0	4.76			$ 32.7
50	11.305			$ 35.4
102	18.1118			$ 33.5
150	24.395			$ 36.2
202	31.2018			
226	34.3434			



Calculations:

0.1309	10.2578	28.0668	28.94955		
4.76					
		22.14046	**Total Shipping Distance**		
		0.1032	214.5393		
0.0278	26.90046				
	9.89146	10.417222			
			37		9.6033
			37		28.1097

Table C-1. Trials to find the optimum number of terminals (250 MW straw)

Number of Terminals	Total Shipping Distance (km)
3	219
4	216
5	214
6	215
7	216
8	218
9	220

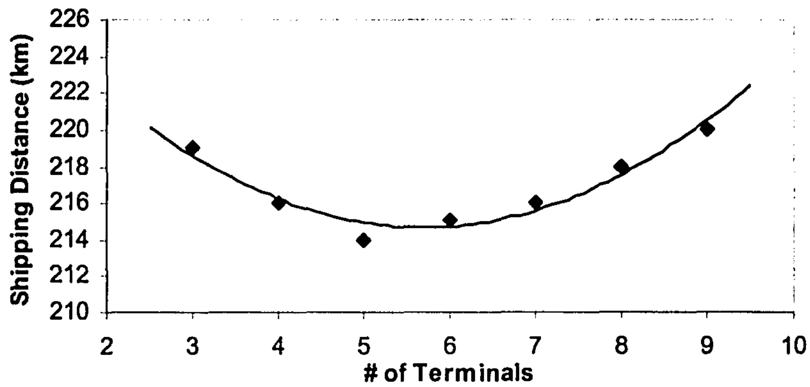


Figure C-1. Total shipping distance vs. number of rail trans-shipment for a 250 straw plant.

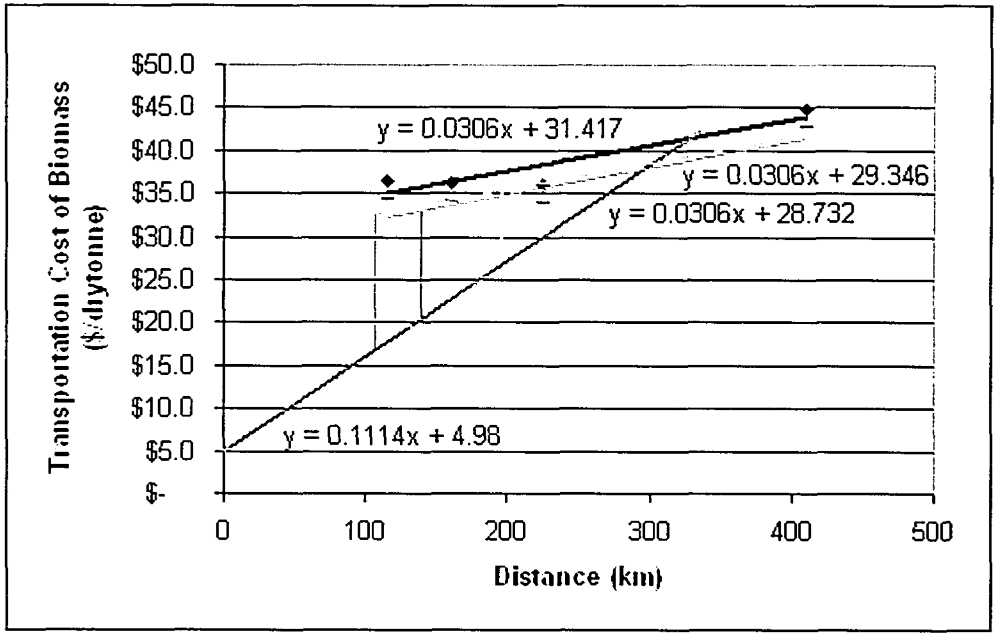
Spreadsheet C-2. Calculations for finding the optimum number of trans-shipment terminals (130 MW wood chips).

DVC calculations (Rail)
Cost vs. Distance (Wood chips)

Dist. (km)	CDN ($)	CDN ($)	CDN ($)
160	$ 14.46	$ 36.16	$ 33.47
225	$ 14.35	$ 36.05	$ 33.37
115	$ 14.77	$ 36.47	$ 33.78
410	$ 23.12	$ 44.81	$ 42.13

DVC calculations (Truck)

0	4.98		CDN ($)
5	5.537		$ 34.09
10	6.094		$ 33.98
15	6.651		$ 34.40
20	7.208		$ 42.74
25	7.765	197.0423	
30	8.322		
35	8.879		
40	9.436		
45	9.993		
50	10.55		
55	11.107		
60	11.664		
65	12.221		
75	13.335		
80	13.892		
85	14.449		
90	15.006		
95	15.563		
100	16.12		
190	26.146		
195	26.703		
200	27.26		



Calculations:

197.0423	26.9258				
197.0423	36.6466		**Intersection Distance**		
		24.3664	301.5644		
139	20.4646	0.0808			
139	32.9854			16.8998	32.6206
				29.3464	
107	16.8998				
107	32.6206			19.6256	

Table C-2. Trials to find the optimum number of terminals (130 MW wood chips).

Number of Terminals	Intersection (km)
3	327
4	306
5	300
6	294
7	296
8	297
9	298
10	302

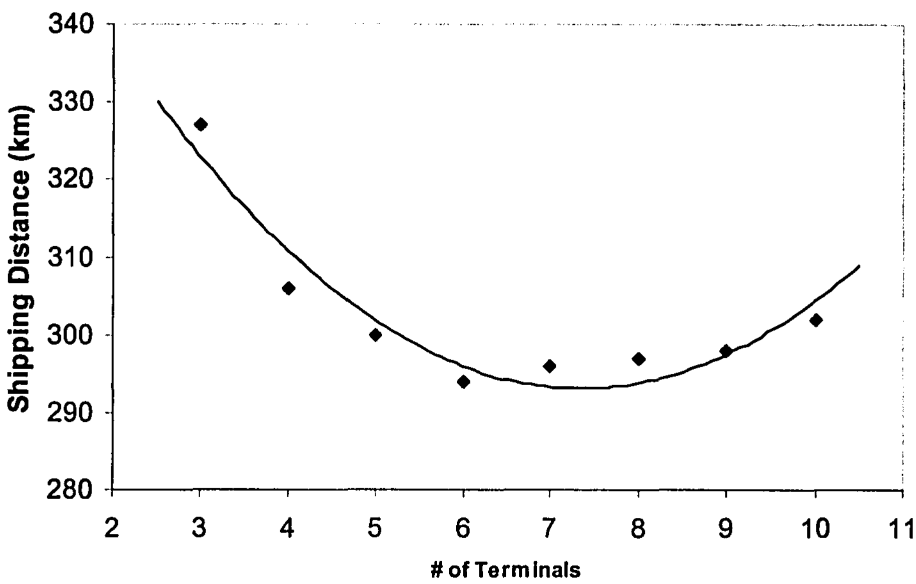


Figure C-1. Total shipping distance vs. number of rail trans-shipment for a 130 MW wood chips plant.

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