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The Relative Cost of Biomass Energy Transport

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Abstract

Logistics cost, the cost of moving feedstock or products, is a key component of the overall cost of recovering energy from biomass. In this study, we calculate for small- and large-project sizes, the relative cost of transportation by truck, rail, ship, and pipeline for three biomass feedstocks, by truck and pipeline for ethanol, and by transmission line for electrical power. Distance fixed costs (loading and unloading) and distance variable costs (transport, including power losses during transmission), are calculated for each biomass type and mode of transportation. Costs are normalized to a common basis of a giga Joules of biomass. The relative cost of moving products vs feedstock is an approximate measure of the incentive for location of biomass processing at the source of biomass, rather than at the point of ultimate consumption of produced energy. In general, the cost of transporting biomass is more than the cost of transporting its energy products. The gap in cost for transporting biomass vs power is significantly higher than the incremental cost of building and operating a power plant remote from a transmission grid. The cost of power transmission and ethanol transport by pipeline is highly dependent on scale of project. Transport of ethanol by truck has a lower cost than by pipeline up to capacities of 1800 t/d. The high cost of transshipment to a ship precludes shipping from being an economical mode of transport for distances less than 800 km (woodchips) and 1500 km (baled agricultural residues).

Index Entries: Biomass transportation; ethanol transport; pipeline transport; power transmission; rail transport; ship transport; transportation cost; truck transport.

Introduction

Biomass can be used as a power source either directly, such as by combustion or gasification to generate electricity, or by creating a fuel such as ethanol, which can be used to power a vehicle. Significant use of biomass as an energy source will require the collection of biomass from the field, for example, agricultural or forestry residues or purpose grown crops. Many field sources of biomass are, by their nature, remote from the

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population centers that will use the produced energy. Thus, developers of such biomass projects will have the alternative of moving the biomass to a plant near the energy consumer, or moving the produced energy from a remote biomass processing plant.

Factors affecting location of biomass plants are both noneconomic and economic. Noneconomic factors include community concerns about traffic congestion and possible emissions such as dust or odors. Economic factors include the relative transportation cost of biomass vs produced energy, the cost of constructing and operating a plant in a location remote from rather than near population centers, and the potential benefit from large-scale integrated processing of biomass, for example, a multiproduct biomass refinery. In this article, we focus on the relative transportation cost of biomass and its energy products to provide a database against which other economic and noneconomic factors can be weighed.

Two cost components are critical in analyzing transportation cost: distance variable costs (DVC), the component that is directly dependent on the distance traveled, and distance fixed costs (DFC), which are independent of the distance traveled. DVC depends on the transportation mode and the specific location; an example is the "per ton kilometer" cost of trucking or rail shipment. DFC depends on the type of biomass being transported and the equipment and contractual arrangements involved, which are both case specific; examples include the cost of loading and unloading biomass from a truck, railcar, or ship. Hence, DFC will vary based on the specific form of biomass to a far greater extent than DVC. For example, this study is based on large round bales of stover or straw, which would require different treatment for transshipment from truck to rail than woodchips. The impact of DFC on overall transportation cost diminishes with increasing distance.

Biomass transportation costs are often reported in units that do not relate to the true determinant of cost of transport, for example, cost dry/ton/kilometer for trucking. In reality, a trucker is not concerned with the number of dry metric tons moved, but rather the total number of actual metric tons as road limits, and hence truck-load limits are based on total weight of material moved. Thus, increases in the moisture level of biomass reduce the amount of dry metric tons per load, and as trucking costs are charged per actual metric ton, the calculated transport cost per dry metric ton will vary for every biomass source.

For truck, rail, and ship transport, mass is the primary factor setting the cost of shipment, although for low density loads volume can become the limiting factor. This has been previously noted for straw shipments by truck *(1)* and railcar *(2)*. For pipelines transporting a single phase liquid, for example ethanol, liquid volume is the primary factor, whereas for two-phase slurry pipelines carrying biomass the amount of dry matter is the primary factor, because moisture level reaches equilibrium during transport *(3)*. For electrical power, the primary factor for costing is the power or

Table 1
Biomass Properties

	Straw	Stover	Woodchips from FHR
Moisture content (%)	15 *(1)*	15 *(5)*	45 *(1)*
Hydrogen content (wt%) *(12)*	5.46	5.46	6.08
Bulk density (dry kg/m^3)	140 *(1)*	145 *(5)*	350 *(1)*
HHV (dry basis [MJ/kg]) *(13)*	18	18	20
LHV (MJ/kg) *(14)*	13.9	13.9	8.8
Gross yield (actual t [GJ/ha])[a]	0.440 *(1)*	0.882 *(5)*	0.449 *(1)*
Gross yield (GJ/ha)	6.12	12.25	3.95
Transport form	Bale	Bale	Chips

[a]Gross hectares refers to the total land area, including towns, roads, and other nonagriculturally productive area.

energy carried in the line, i.e., MW or MWh. In this study, we relate all transport cost for biomass and its conversion products to the primary factor governing the cost, and then apply these relations to calculate the cost of moving biomass or the amount of product that can be produced from that biomass.

Modeling Biomass Transportation Costs

Biomass Sources

We study three biomass residue sources: straw from grain in western Canada, corn stover from the midwestern United States, and woodchips from forest harvest residues (FHR) (the limbs and tops of trees harvested for pulp or lumber) from the boreal forest in Canada. These three sources were selected because they represent large sources of field biomass for which supply is contiguous over large areas. The two agricultural residues are somewhat remote from major centers of population, whereas boreal forest operations are often very remote, for instance across the northern half of Provinces in Canada. Table 1 identifies the properties of the biomass used in this study.

Processing Alternatives

We analyze two conversion alternatives for each biomass source, electrical power and ethanol. Electrical power is produced by direct combustion of biomass; thermal efficiency figures are based on the performance of the largest biomass boiler, the Alholmens 240-MW power plant in Pietarsaari, Finland *(4)*. Values for ethanol production through fermentation are derived from previous studies for both corn stover and woodchips from the US National Renewable Energy Laboratory (NREL) *(5,6)*.

NREL estimates show a significantly lower conversion efficiency for woody biomass as compared with agricultural residues.

Each processing alternative was evaluated at both small and large scale. For all three biomass sources the small-scale plant size is identical in biomass energy input. The small power plant processes enough biomass to produce 50 MW (gross) power. Differing values of lower heating value (LHV) result in a higher biomass requirement from woodchips than from straw to produce an equivalent amount of power. The small-scale ethanol plant processes the same mass of biomass feed as required to produce 50 MW of power. For straw and stover the large-scale plant is a 500 MW (gross) power plant or an ethanol plant processing the same amount of biomass to ethanol. For woodchips from FHR the large-scale plant is a 150 MW (gross) power plant or an ethanol plant processing the same amount of biomass to ethanol. The difference in large-scale size reflects previous studies of optimum size of biomass processing *(1)*: larger processing plants are economic for biomass sources with a lower overall transportation cost. Higher gross yield of energy (the energy content of the biomass available in the total draw area) is a key factor in transportation costs. Compared with woodchips from FHR, straw has a 50% higher energy yield per gross hectare (gross hectare refers to the total draw area for the biomass), and stover has 300% the energy yield of woodchips from FHR. The higher energy yield for agricultural residue justifies the 500 MW plant size vs 150 MW for FHR. Table 2 outlines the processing parameters used in this study.

Transportation Modes

We evaluate a short and a long transport distance, i.e., the assumed distance between the centers of the biomass collection area and the product usage area, arbitrarily chosen as 100 and 500 km. The study is not focused on moving biomass to a centralized processing plant, but rather moving either biomass or its products from source to market. All costs in this study are reported in 2004 US dollars.

Four modes of biomass transportation are evaluated in this study:

- **Truck transport**—straw is transported using a 20 t capacity flatbed truck, and woodchips using a 40 t chip van. Costs for both are derived from previously reported actual costs in western Canada, where bale and chip movement are routine *(1)*. We note, however, that transport of woodchips is subject to long-term high volume contracts, whereas straw movement is seasonal and usually moves a much lower volume of biomass per contract. Hence, straw costs in this study might be higher than if long-term contracts to move straw on a year round basis were used to support a straw processing industry, as such contracts ensure high equipment utilization.
- **Truck plus rail transport—**straw and woodchips are moved to a rail siding where they are loaded on a unit train for transport over the

Table 2

Processing plant parameters	Small		Large	
	Straw/stover	Woodchip	Straw/stover	Woodchip
Biomass				
Biomass feed (actual Mt/yr)	0.269	0.427	2.69	1.28
Draw area (km^2)	6125	9500	61,250	28,500
Average driving distance (km)	55	68	173	118
Ethanol				
Ethanol yield (t/d)	174	83	1743	315
Ethanol yield as fraction of dry mass (wt%) *(5)*	25	11.6	25	11.6
Ethanol pipeline diameter (in.) *(10)*	4	3	8	4
Power				
Capacity (mW)	50	50	500	150
Thermal efficiency (LHV [%]) *(4)*	38	38	38	38
Availability (%)	90	90	90	90
Parasitic load (%)	8.5	8.5	8.5	8.5

specified distance. Costs for the truck transport are calculated with the average trucking distance calculated from the biomass gross yield, assuming that the biomass source is contiguously available around the railhead. A rectilinear road system, common in the western United States and Canada, is assumed. Costs for rail are taken from a previous study of rail transport *(2)*. Straw transport by rail is assumed to be on flatbed cars without tarping; however, it would need to be verified whether a unit train of uncovered straw would present an unacceptable risk of fire. Truck plus rail transport would only make sense for the long distance case. At 100 km the collection area of biomass is so large that the cost of transshipping from truck to rail cannot be recovered by the savings in DVC *(2)*.

- **Truck plus pipeline transport—**straw and woodchips are moved to a pipeline inlet where they are slurried with water. Costs for truck transport to the pipeline inlet are identical to those for rail transport. Pipeline costs are derived from a previous study *(7)*. Note that pipeline costs show a significant economy of scale, whereas truck and rail transport do not. The previous study noted that pipeline transport of biomass is not compatible with a combustion-based utilization of the biomass, because uptake of carrier fluid by the biomass reduces the LHV. Hence, this transportation mode would only be compatible in this study with the production of ethanol. Like rail transport, this option is only evaluated for the long distance case.

- **Truck plus ship transport—**straw and woodchips are moved to a ship where they are loaded for transport. The draw area for biomass is assumed to surround the ship loading area, an ideal case. Costs for truck transport to the ship are identical to those for rail transport, and ship costs are derived from a previous study *(8)*. Like rail transport, this option is only evaluated for the long distance case.

For power generation cases we assume that a power plant using the biomass is located remote from existing transmission lines, and we develop the cost of transmission based on the construction and operation of a dedicated line. Capital and operating costs for transmission lines are developed from detailed data from an integrated power company (Manitoba Hydro, Winnipeg, Canada). A single circuit 230 kV transmission line is used up to 200 MW, and capital cost is virtually independent of capacity. Larger capacity transmission lines use multiple circuits to reduce line loss of power. Thus, at 500 MW a two circuit 230 kV line would be built, at a premium of 50% in capital cost to a single circuit 200 MW line. A 12% pretax return is applied in calculating capital recovery. Operating costs are line losses, which are proportional to the square of the line capacity in megawatt, and maintenance costs. Maintenance cost for transmission lines is primarily vegetation control and is independent of capacity.

Two modes of ethanol transportation are evaluated in this study:

- **Truck—**the study basis is a tandem tanker carrying 40 t of ethanol. Costs are developed from industry charge rates for long-term contracts *(9)* and are based on a truck loading and unloading time of 45 min each and an average transport speed of 100 km/h.
- **Pipeline—**the cost of ethanol pipelining was developed from an analysis of capital and operating costs. Pipeline capital costs are based on discussions with a major contractor *(10)*; a 12% pretax return is used in calculating capital recovery. Pump station number and power requirement are based on detailed calculations of pressure drop; a power cost of $60 MW/h is used in this study. Annual maintenance costs are estimated based on percentages of capital cost drawn from industry norms: 0.5% for the pipeline and 3% for pumping stations.

Results

Transportation Cost Factors

Table 3 lists the DVC and DFC for all modes of transportation in this study. The units for DVC and DVC reflect the actual basis by which the cost of transportation is primarily affected, for example, actual mass for truck transport, volume for ethanol pipelining, and mass of dry matter for biomass pipelining. The economy of scale is negligible for some modes of

Table 3
Distance Variable and Distance Fixed Transportation Parameters[a]

Mode	Item transported	DVC	Units	DFC	Units
Truck	Straw/stover *(2)*	0.12	$ Actual t/km	4.39	$/Actual t
	Woodchips *(2)*	0.07	$ Actual t/km	3.01	$/Actual t
	Ethanol *(9)*	0.05	$ Actual t/km	3.86	$/Actual t
Rail *(2)*	Straw/stover	0.023	$ Actual t/km	14.15	$/Actual t
	Woodchips	0.017	$ Actual t/km	5.48	$/Actual t
Ship *(8)*	Straw/stover	0.01	$ Actual t/km	34.01	$/Actual t
	Woodchips	0.01	$ Actual t/km	11.15	$/Actual t
Pipeline	Biomass[b] *(7)*	$23.4\ C^{-0.4086}$	$ Dry t/km	$4{,}19{,}000\ C^{-0.8656}$	$/Dry t
	Ethanol[c] *(10)*	$4.13\ E_m^{-0.5885}$	$ t Ethanol/km	0	$/t Ethanol
	Ethanol[d] *(10)*	$0.062\ E_v^{-0.5885}$	$/L/km	0	$/L
Power *(15)*	46 MW net	321	$/MW/km	0	$/MW
	137 MW net	195	$/MW/km	0	$/MW
	458 MW net	208	$/MW/km	0	$/MW
	46 MW net	0.04	$/MWh/km	0	$/MWh
	137 MW net	0.02	$/MWh/km	0	$/MWh
	458 MW net	0.03	$/MWh/km	0	$/MWh

[a]Source data have been adjusted to consistent units and a common currency (2004 US dollars).
[b]C, pipeline capacity in dry metric tons biomass per year.
[c]E_m, pipeline capacity in metric tons of ethanol produced per day.
[d]E_v, pipeline capacity in liters of ethanol produced per day.

transport, such as truck, rail, and ship: more biomass means more loads at a set cost per load that depends on distance traveled. The economy of scale is strong for pipelining, as reflected in the low exponent relating DVC to capacity. Power transmission show a discontinuity in cost between 150 and 500 MW because the line design changes from single circuit to double circuit.

DFC values in Table 3 show a wide range. Ship transport, for example, has the lowest DVC cost, but the cost of getting biomass onto and off a ship is high relative to the cost of loading a truck. Rail cars are intermediate. Note that for both ship and rail the DFC for straw/stover is significantly higher than for woodchips. Woodchips lend themselves to bulk handling by methods such as conveying or pneumatic transfer, whereas straw/stover is moved as a large bale. As noted earlier, pipeline transport of biomass can only be used for aqueous-based processing, and DFC for pipelining is low because the cost of slurrying biomass is not incremental to the overall processing cost. Rather, slurrying of biomass can be thought of as shifting equipment from the processing plant to the pipeline inlet. Hence, DFC for pipeline transport of biomass reflects incremental labor, typically one extra person at the pipeline inlet compared with the staffing required for biomass receipt by truck or rail at a central pipeline facility *(11)*. An ethanol pipeline located within a biomass processing plant would have no DFC: pipelines would typically be connected directly to product storage tanks. Similarly, power transmission has no incremental DFC.

Relative Transportation Costs

The transportation cost factors were then used to calculate the cost of transporting biomass or the equivalent amount of ethanol or power that could be produced from that biomass for eight cases: straw/stover and woodchips from FHR to ethanol and power at large and small scale. Results are normalized to the transport cost per unit of energy in the incoming biomass, and are shown in Figs. 1–4.

Many observations can be drawn from Figs. 1 to 4; we highlight some key observations.

- In all cases a product transportation option is available that is significantly lower than the cost of moving biomass. Two factors contribute to this: biomass has a low energy density, and the energy produced from biomass is lower than the energy in the biomass as a result of conversion losses. The latter is especially true for ethanol from wood, which has a very low conversion efficiency compared with ethanol from straw or power from any biomass source. Note also that at 500 km the cost of transporting biomass by truck is more than $4/GJ, a significant cost considering that the current wholesale price of natural gas is about $6–8/GJ in North America.

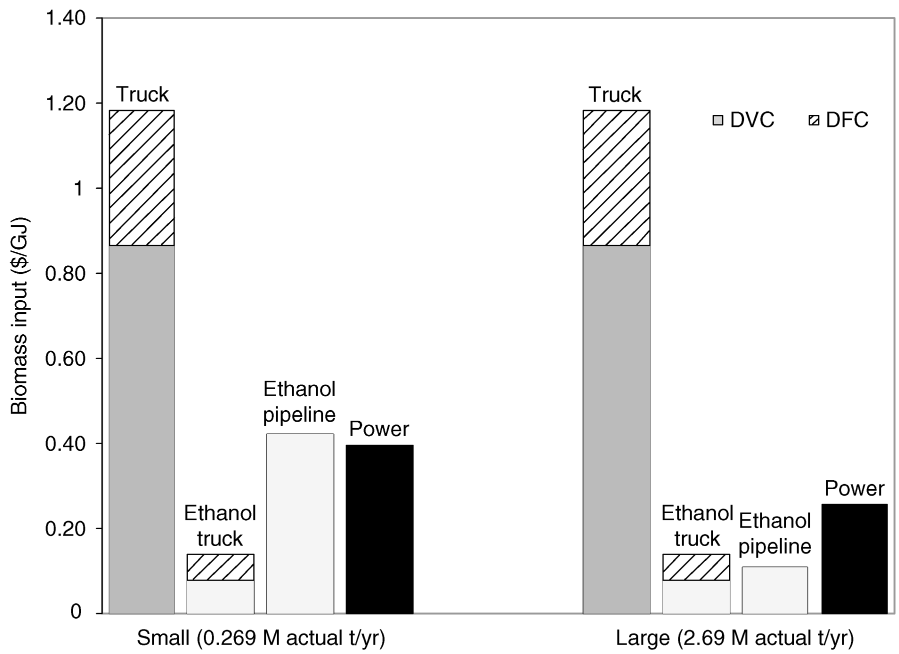


Fig. 1. Agricultural residue transportation costs for biomass and products more than 100 km.

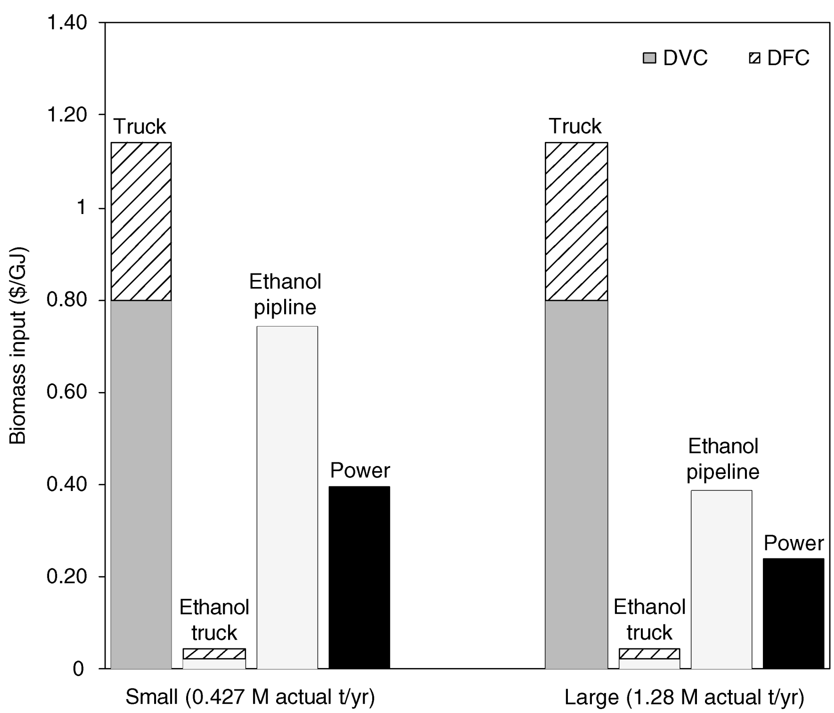


Fig. 2. Woodchip transportation costs for biomass and products more than 100 km.

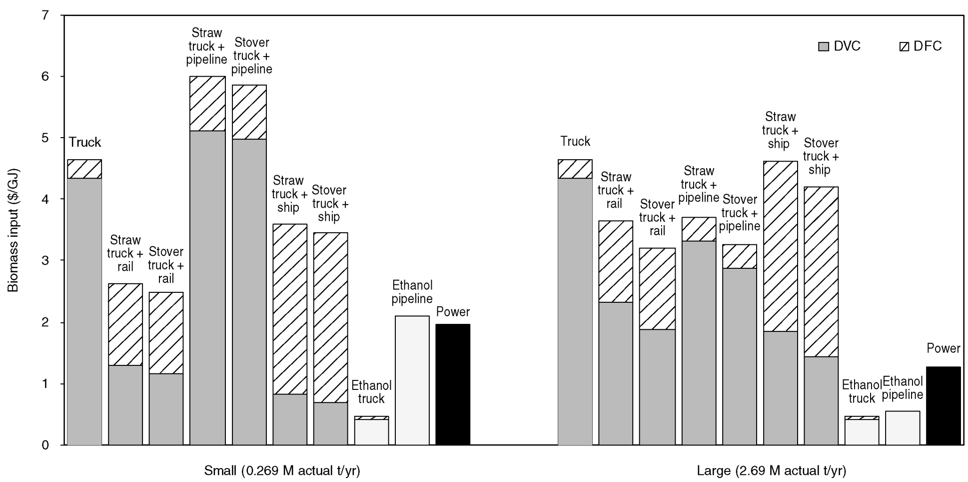


Fig. 3. Agricultural residue transportation costs for biomass and products more than 500 km.

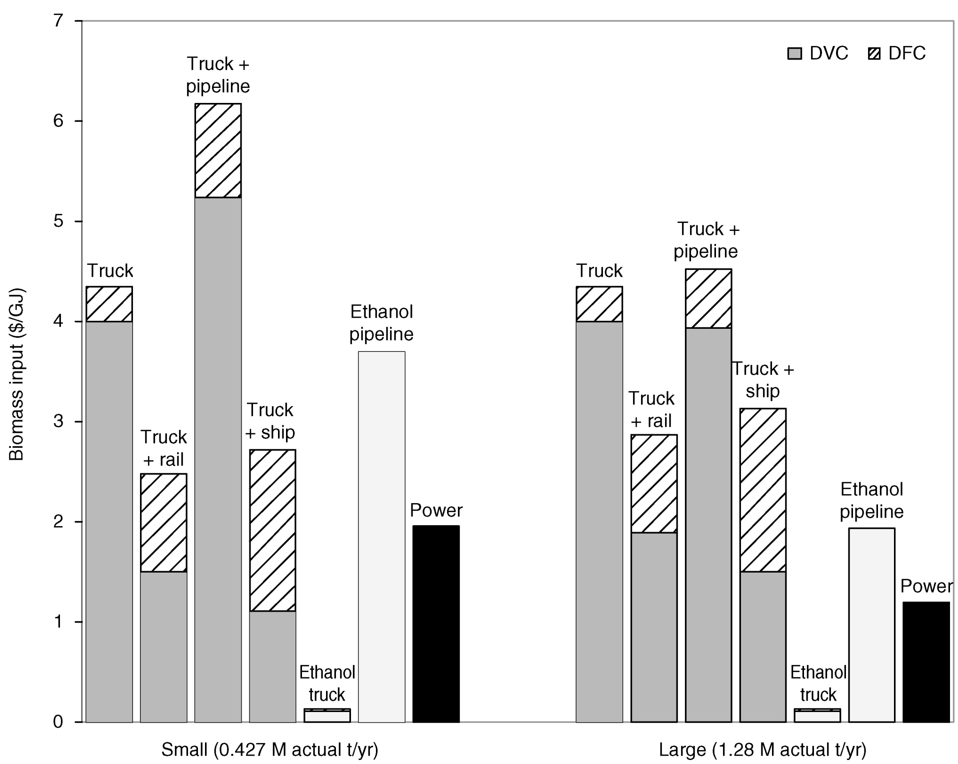


Fig. 4. Woodchip transportation costs for biomass and products more than 500 km.

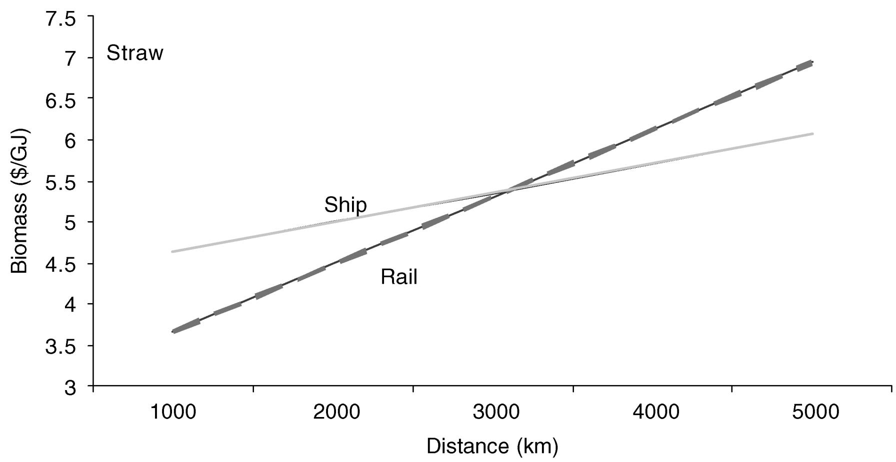
- If rail transport is available it is more economical to transship biomass to rail for transport distances of 500 km.
- Pipelining of biomass is not economical at small scale, nor at the large-scale for wood chips, 1900 dry t/d of biomass. It is competitive with rail transport at large-scale for straw, i.e., about 2.5 Mt/yr).
- Ship transport is not economical relative to rail at a transport distance of 500 km because the high DFC cost offsets the benefit of a low DVC.
- Pipelining of ethanol is uneconomical from small-scale plants, and is about as economical as truck transport for the large-scale straw/stover to ethanol plant in this study, producing 1700 t/d (2.3 ML/d) of ethanol. Ethanol pipelining does not have a DVC, so pipelining is more economical than truck shipment for the large case at 100 km, and slightly less economical at 500 km. From Table 3 one can calculate that the DVC for pipelining ethanol is lower than truck haul more than 1800 t/d ethanol, making pipelining more economical than truck hauling at any distance.
- The transmission lines for the small and large woodchip power plants are identical, and therefore have the same capital and maintenance costs. However, line losses increase with the square of the power transmitted. The large-plant transmission cost is 60% of the small-plant transmission cost.

The high DFC for loading and unloading biomass from ships means that long distances are required for the saving in DVC to offset the DFC. Figure 5 shows the cost of rail vs ship transport of biomass as a function of distance. Shipping of straw incurs a very high DFC, as noted earlier, and a shipping distance of about 1500 km is required before the lower DVC of shipping offsets the incremental DFC. DFC for woodchips is lower, and shipping is more economical than rail transport at a distance of about 800 km.

Discussion

Transportation is a cost element in any energy project, and this is especially true for biomass because of the lower energy density compared with fossil fuels. Woodchips with a moisture content of 45% have an LHV of less than 10 MJ/kg, whereas the comparable figure for surface-mined coal in western North America is about 20 MJ/kg. However, there are at least two incentives for aggregating large amounts of biomass in an energy project: the economy of scale in processing, and the ability to create a multiproduct integrated biorefinery maximizing the production of higher value products and using all of the energy in the biomass. Assessing these tradeoffs requires a careful analysis of the cost of moving both biomass and its products.

For example, the relative cost of transporting biomass and its products can be used to do some preliminary screening of plant-site location.



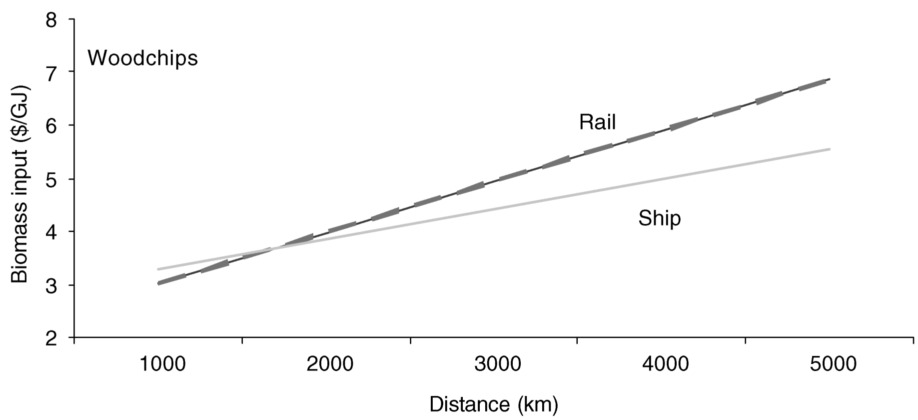


Fig. 5. Determination of the minimum distance where the cost per GJ biomass input is lower for ship than for rail transport.

A previous detailed study of producing power at optimum plant size from biomass in western Canada *(1)* showed a total power plant operating cost including administration, operating labor, maintenance, and capital recovery of $25/MWh for straw and $34 for woodchips, adjusted to 2004 USD; the difference arises from the larger optimum plant size for straw relative to FHR. This range of cost is equivalent to $2.40–3.20/GJ in the biomass for a thermal efficiency of the power plant of 34%, the value used in the study. As a general guideline, plants built in remote areas will have capital and operating costs that are 10% higher than those built near a large population center, because of the need to build an access road and a camp to house construction labor, and the need for higher salaries to attract operating and maintenance staff to a remote setting *(10)*. At 10% premium the impact is therefore, about $0.24–0.32 of increased cost per GJ of biomass. The cost savings from transporting power rather than biomass for the two large-scale cases is more than $2/GJ in the biomass at 500 km, and about $1 at 100 km. Hence, the cost of remote construction is not likely to be the deciding factor for moving biomass from a remote area to a location adjacent to an existing transmission grid: it is cheaper to move the power and pay the location premium.

Ethanol production raises two transportation issues. First, yield of ethanol per metric ton of biomass is low, 25% on a dry basis for straw and 12% on a dry basis for woodchips. Factoring in moisture content, the mass of biomass moved is about five times higher than the ethanol produced from straw, and 15 times higher for woodchips. At large scale, 1800 t/d, ethanol pipelining becomes more economical than truck transport at any distance. This scale is too large to be economically supplied by a low-gross yield biomass such as woodchips from FHR. In addition, ethanol production produces large amounts of unconverted biomass. Transporting biomass to a distant ethanol plant might require that the residue from processing be transported back to the point of origin, creating a further disincentive.

A biorefinery has the potential to increase the value of biomass by producing fuels, chemicals, and power, for example, ethanol form fermentation coupled with combustion or gasification of lignin to produce power. If biomass is being moved an average of 100 km to a biorefinery the integration would have to yield a value of $1/GJ in the biomass to justify the transportation premium.

Conclusions

Transportation costs for biomass and its products have a distance fixed component that is incurred regardless of the distance traveled, and a distance variable component that is directly related to the distance traveled. Both factors must be included in an analysis of transportation costs. Some modes of transportation, for example, trucking, have a negligible economy of scale and DVC is constant; others such as pipelining have a high economy of scale, and DVC is a function of capacity. Shipping of biomass has a low DVC but a high DFC, and hence is not economic below 800 km (woodchips) and 1500 km (straw/stover). Transshipment from truck to rail is economical at 500 km for both woodchips and straw/stover if rail lines are available. Ethanol transport by pipeline is more economical than trucking at production rates of 1800 t/d of ethanol; this is well above the economic size of producing ethanol from a dispersed low-yield biomass source like FHR. The gap in cost between the cost of transporting power and biomass is far more than the expected higher cost of building and operating a power plant in a location remote from an existing transmission grid.

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References

1. Kumar, A., Cameron, J., and Flynn, P. (2003), *J. Biomass Bioenergy* **24,** 445–464.
2. Mahmudi, H. and Flynn, P. (2006), *J. Appl. Biochem. Biotechnol.* **129–132,** 88–103.
3. Kumar, A., Cameron, J., and Flynn, P. (2004), *J. Appl. Biochem. Biotechnol.* **113,** 27–40.
4. Flynn, P. and Kumar, A. (2005), Trip Report, Pietarsaari, Finland. University of Alberta, Canada (May 1, 2006). www.biocap.ca/files/reports.
5. Aden, A., Ruth, M., Ibsen, K. Lignocellulosic biomass to ethanol process design and economics utilizzing co-carrent diulte acid prehydrolsis for corn stoner, TP-5-32438 (2002), National Renewable Energy Laboratory, Golden, Colorado.
6. Wooley, R., Ruth, M., Sheehan, J., and Ibsen, K. (1999), Lignocellulosic biomass to ethanol process design and economics utilizing co-corrent dilute acid prehydrolysis and enzymatic hydrolysis—current and futuristic scenarios, TP-580-26157. National Renewable Energy Laboratory, Golden, Colorado.
7. Kumar, A., Cameron, J., and Flynn, P. (2005), *J. Bioresour. Technol.* **96,** 819–829.
8. Borjesson, P. and Gustavsson, L. (1996), *J. Energy* **21,** 747–764.
9. Taylor, J. (2002), Regional Manager of Gibson's Trucking Company, Alberta, Canada, personal communication.
10. Williams, D. (2002), Chief Estimator for Bantrel Corporation (an affiliate of Bechtel), Edmonton, Calgary, Alberta, Canada, personal communication.
11. Ghafoori, E. and Feddes, J. (2005), Pipeline vs beef transport of beef cattle manure. ASAE Pacific Northwest Section Meeting Presentation, PNW05-1012, Lethbridge, Alberta, Canada.
12. Rao, M., Singh, S., Sodha, M., Dubey, A., and Shyam, M. (2004), *J. Biomass Bioenergy* **27,** 155–171.
13. Cameron, J., Kumar, A., and Flynn, P. (2004), ASAE/CSAE Annual International Meeting, PN 048039, Ottawa, Ontario, Canada.
14. Van den Broek, R., Faaij, A., and Van Wijk, A. (1995), Department of Science, Technology and Society, Utrecht University, Netherlands.
15. Mailey, S. (2006), Transmission information engineer, Manitoba Hydro, Winnipeg, Manitoba, Canada, personal communication.