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Large-Scale Ethanol Fermentation Through Pipeline Delivery of Biomass

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Abstract

Issues of traffic congestion and community acceptance limit the size of biomass-processing plants based on truck delivery to about 2 million (M) dry t/yr or less. In this study, the cost of ethanol from an ethanol fermentation plant processing 2 M dry t/yr of corn stover supplied by truck is compared with that of larger plants in the range of 4–38 M dry t/yr supplied by a combination of trucks plus pipelines. For corn stover, a biomass source with a low yield per gross hectare, the cost of ethanol from larger plants is always higher. For wood chips from the boreal forest, a biomass source with a relatively high yield per gross hectare, a plant processing 14–38 M dry t/yr produces ethanol at a 13% reduction in cost compared with a plant producing 2 M dry t/yr supplied by truck. Processing of value-added products, such as chemicals from lignin, would be enabled by larger-scale plants.

Index Entries: Ethanol fermentation; pipeline delivery; wood chips; corn stover; economies of scale.

Introduction

Biomass projects have unique economics relative to other energy projects: there is an optimum size of a plant. This arises because there are competing cost drivers: increasing scale achieves improved capital efficiency through economies of scale but also increases the average distance that biomass must be transported to the facility. Because transportation of biomass is a major component of overall delivered feedstock cost, ultimately a size is reached at which further increases are not economic (see, e.g., refs. *1–5*).

However, most biomass projects are built well below optimum size because of either biomass availability or transportation constraints. Field-produced biomass (as opposed to mill residues) starts its trip to

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a processing facility on a truck, and usually highway truck transport is the selected mode for transport all the way from the field to the plant. Because truck carrying capacity is limited to 20–40 t, economically sized biomass plants require a high frequency of delivery *(6,7)*. Community resistance and/or road congestion can hence become a limiting factor before the economic optimum size of a biomass-processing plant is achieved. For example, Kumar et al. *(5)* calculated that the optimum size of a power plant processing wood chips from harvesting the whole forest is 900 MW. This size of plant would require 4.3 million (M) dry t/yr of fuel, or one 36 t chip van delivery every 4 min. It is difficult to imagine a community or a local road system that could accept this traffic density. For similar reasons, much of the analysis of ethanol fermentation from corn stover completed by the US National Renewable Energy Laboratory (NREL) in Colorado has focused on ethanol processing plants that are very small compared to a typical oil refinery. Many NREL studies have used a base case feed rate of 0.73 M dry t/yr (2000 dry t/d) because of transportation constraints (see, e.g., refs. *8* and *9*).

Slurry pipelining is an alternative means of delivering biomass to processing plants. Kumar et al. *(10)* evaluated pipeline delivery of wood chips to a power plant. Transportation costs are lower for one-way pipeline (without carrier fluid return) than truck delivery at rates above 0.5 M dry t/yr. However, absorption of water reduces the lower heating value of the wood chips, which is the available energy in a combustion process, by more than 40%, which more than offsets the reduction in transportation cost.

Uptake of carrier fluid by biomass is not an issue in processes such as fermentation that are water based. In a subsequent study, Kumar et al. *(7)* showed that pipeline transport of corn stover to an ethanol fermentation plant had a lower transportation cost than truck delivery at rates in excess of 0.75 M dry t/yr of corn stover. They noted that multiple pipelines delivering to a larger ethanol processing facility could also potentially gain from economies of scale in the processing plant as well. In addition to economy of scale, the ability to convert byproducts such as lignin into useful products (power or chemicals) would also be enhanced by a larger-scale plant. For example, Wallace et al. *(11)* notes combustion of lignin in small-scale ethanol plants as a particular source of diseconomy.

The purpose of the present study was to screen two alternatives for processing of biomass to ethanol. The first is processing of truck-delivered corn stover or wood chips in smaller processing plants, with a capacity of 2 M dry t/yr. The second is truck delivery of biomass to pipeline inlets, each with a capacity of 2 M dry t/yr, which then transport the biomass as a water slurry to a central large ethanol processing plant. Total transport distance for biomass in the second alternative is higher; the key question is, does higher economy of scale in the fermentation plant more than offset the higher transportation cost? Note that 2 M dry t of biomass/yr equates to one truck delivery every 5–10 min, and we assume this as a limit

Table 1
DVC of Transportation of Biomass

Biomass	DVC ($/[dry t · km])
Straw *(14)*	0.1348
Straw *(5)*	0.1309
Wood chips	
Long-term supply *(10)*	0.1114
Short-term supply *(10)*	0.1524
Corn stover *(8,16)*	0.1167
Corn stover *(17)*	0.1045
Corn stover *(12)*	
Round bales	0.0527
Rectangular bales	0.0596
Switchgrass *(13)*	0.1984

of community acceptance. This assumption is arbitrary; in specific cases, limits might be higher if a delivery site is adjacent to a major highway, and lower if the site is near or requires transport through a community.

Our study draws on previous design work by NREL of an ethanol plant processing 0.73 M dry t/yr of corn stover *(8)*, and on two previous studies of pipelining biomass *(7,10)*. The NREL study includes a specific analysis of scale factors by equipment type, which allows an assessment of the impact of scale for portions of the ethanol plant. In this screening study, we assume identical investment in the fermentation plant for both corn stover and wood chips; future study could be based on a more detailed assessment of the capital costs of wood chip fermentation. Note that all cost figures in this study, even when cited from the literature, have been adjusted for inflation to a common year 2000 US dollar basis. Costs include a capital recovery factor based on a return of 10%.

Optimum Size for Truck Delivery of Corn Stover and Wood Chips to a Fermentation Plant in Absence of Constraints

Table 1 shows the range of the distance variable cost (DVC) component of truck transport of biomass reported in the literature, in dollars per dry tonne per kilometer. Estimates of the truck DVC of low-density biomass such as straw and corn stover vary widely. The low value of 5.3¢ is from a US Oak Ridge National Laboratory (ORNL) theoretical study *(12)*. The high value of 19.8¢ is from a study by Marrison and Larson *(13)*. Values by Jenkins et al. *(14)*, Kumar et al. *(5)*, and a study by NREL *(8)* are each based on an analysis of actual transportation costs. For wood chips, rates depend on length of contract, Kumar et al. *(7)* discuss the wide range in estimates of DVC for trucking in more depth.

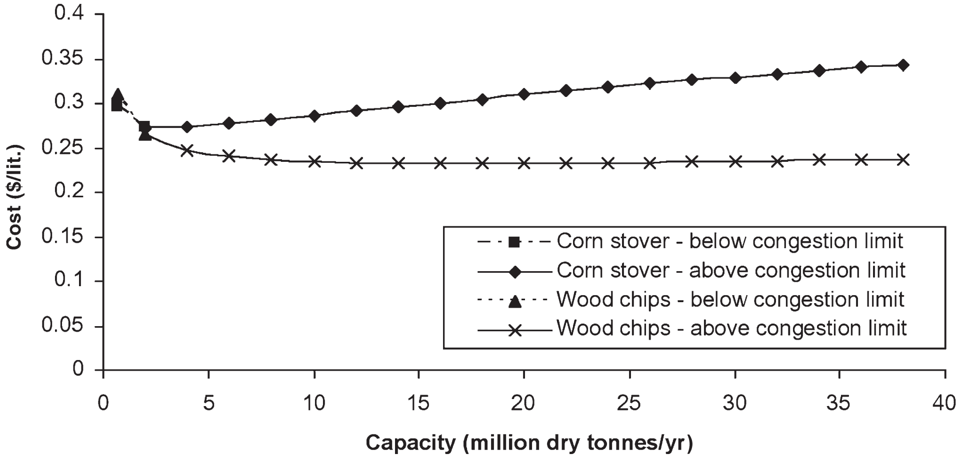

Fig. 1. Cost of ethanol from a fermentation plant supplied by truck delivery.

Correct estimation of DVC is critical to any analysis not only of pipeline vs truck transport but also of optimum biomass plant size, because the critical increasing cost element that has an impact on optimum size is only the distance variable component of transportation cost. In the balance of the present work, we use a DVC of 12.75¢/(dry t · km) for corn stover, which is a blended average of the actual transportation costs for baled agricultural residues cited by Jenkins et al. *(14)*, Kumar et al. *(5)*, and the NREL study *(8)*. The distance fixed cost (DFC) for truck transport of corn stover is estimated at $5.32/dry t *(7)*. Comparable figures for wood chips are a DVC of 11.14¢/(dry t · km) and a DFC of $4.98/dry t. Note that all fixed costs of biomass, including acquisition or harvesting cost, do not affect the calculation of the optimum size of a processing plant *(15)*.

Figure 1 shows the estimated cost of production of ethanol from corn stover and wood chips in a fermentation plant supplied by highway trucks. Ethanol yield per dry tonne of biomass is drawn from Aden et al. *(8)* for corn stover, and Wooley et al. *(9)* for wood chips. Note that the dashed portions of the curves are not practically achievable owing to assumed transportation constraints of community acceptance and road congestion, as discussed earlier. Hence, the theoretical minimum cost of 23.3¢/L of ethanol from truck-delivered wood chips is not attainable; the cost at 0.73 and 2.0 M dry t of corn stover/yr is 29.7 and 27.3¢/L, respectively, and for wood chips is 31.1 and 26.6¢/L. Note that even if traffic congestion constraint were not a limiting factor, the optimum size of an ethanol plant for corn stover would still be about 2 M dry t/yr, because the biomass yield per gross hectare is low and transportation costs that are rising with increasing plant size overwhelm capital savings. Gross hectares refers to the total area from which biomass is drawn including noncultivated land such as roads and communities and land planted with other crops.

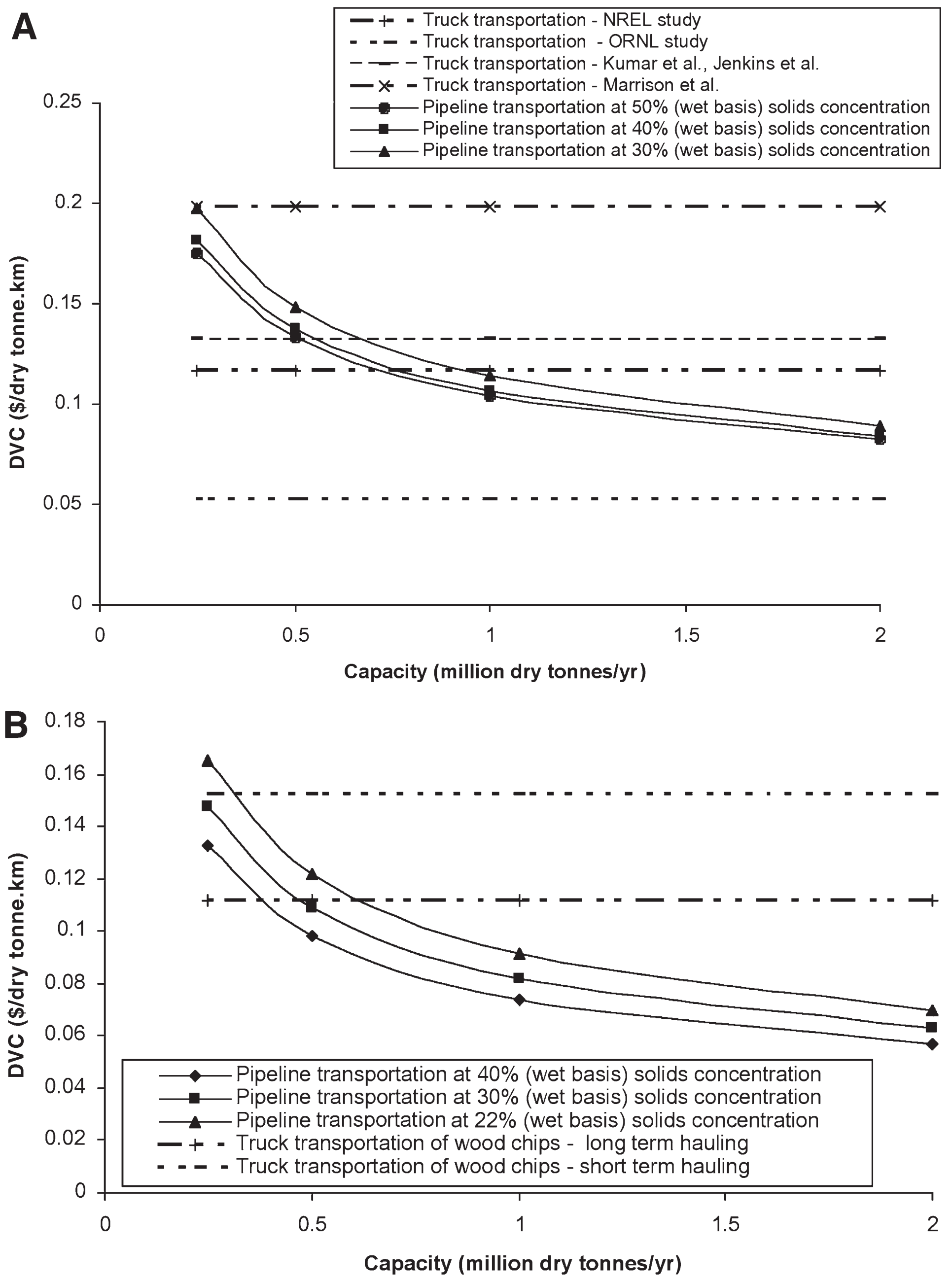

Fig. 2. (A) DVC of transporting corn stover by pipeline; **(B)** DVC of transporting wood chips by pipeline.

Pipelining of Biomass

Figure 2A, B shows the cost of one-way pipelining (no return of carrier fluid) of corn stover and wood chips as a function of the capacity of the pipeline; see Kumar et al. *(7,10)* for details of the cost estimates for pipelining. Note that the concentrations of biomass in water in Fig. 2A, B are based on water-saturated material. Stalk material such as corn stover or straw absorbs water quickly and achieves a moisture level of 80% (*[10,18]*; J. Hettenhaus, personal communication, 2/04), so a 50% slurry of wet corn stover would be 10% dry matter (DM) and 90% water. Uptake of water by wood chips is slower but would reach a level of about 65% water within the typical residence time for pipeline transport *(10)*. A pipeline inlet processing biomass delivered by trucks into a water-based slurry would face the same congestion constraint as an ethanol processing plant, so in Fig. 2A, B the pipeline is limited to a maximum capacity of 2 M dry t/yr.

Figure 2A, B also shows the variable cost of truck transportation of biomass for comparison. Because the biomass is already on a truck when it arrives at the pipeline inlet, the fixed costs of truck transportation, associated with loading and unloading of the truck, have already been incurred. In comparing pipeline transportation costs with truck transportation costs, the critical question is, is the cost of pipelining less than the incremental (distance variable) cost of further truck transport?

Figure 2A, B illustrates why an accurate assessment of DVC for truck transport of biomass is so critical. If the value of DVC for trucking from the ORNL study is realistic, then pipelining of corn stover will never be economic at any practical scale. If, on the other hand, the values of Jenkins et al. *(14)*, Kumar et al. *(10)*, and the NREL study *(8)* are realistic, then pipelining can compete with incremental trucking at capacities above 0.5 and 0.75 M dry t/yr for wood chips and corn stover, respectively. If the values of Marrison and Larson *(13)* are realistic, then pipelining is competitive even at very small capacities.

Configuration of an Ethanol Fermentation Plant Supplied by Pipeline

Figure 3 illustrates a configuration used for comparing the cost of ethanol from smaller plants supplied by trucks vs a larger plant using 38 M dry t/yr of biomass supplied by a combination of truck plus pipeline. Table 2 provides key transportation distances. (Truck hauling from the interstitial areas has been ignored in this screening study.) Note that in the innermost circle in Fig. 3 biomass would be supplied by truck only to the processing plant, whereas in each other circle biomass would be delivered by truck to a pipeline inlet. Circle diameter is a function of gross biomass density, i.e., biomass yield per total hectare, and, hence, is different for wood chips, for which we have assumed a boreal forest density *(5)*, and corn stover, for which we have used data from ORNL *(12)*. Also note that for an annual crop such as corn, the stover is harvested from the entire area each year, whereas for a multiyear crop such as trees, only one-twentieth of the area is harvested each year, based on an assumed fermentation plant life of 20 yr. One can use the distance data in Table 2 to estimate the transportation

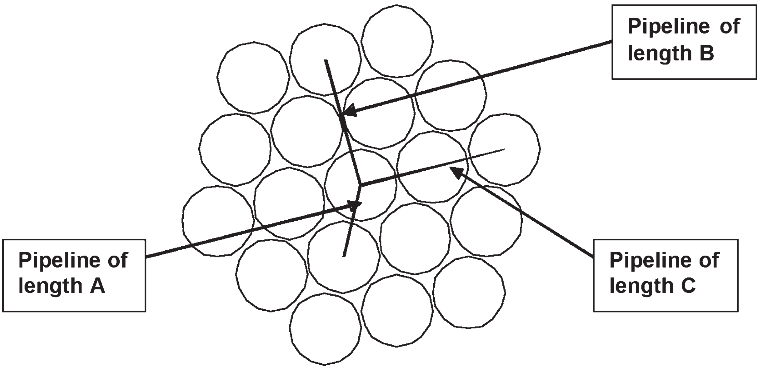

Fig. 3. Sample configuration for 19 truck-based ethanol plants vs one larger facility supplied by truck plus 18 pipelines of three different lengths.

Table 2
Biomass Yield and Truck and Pipeline Distances for Corn Stover and Wood Chips

	Corn stover	Wood chips
Available biomass gross yield (dry t/ha)[a]	2.47[c]	84[d]
Radius of circle containing 2 M dry t/yr biomass (km)	103	28
Average truck haul length per circle (km)	146	39
A—pipeline length (km)	292	78
Residence time in pipeline A (h)[b]	54	15
B—pipeline length (km)	506	135
Residence time in pipeline B (h)[b]	94	25
C—pipeline length (km)	584	156
Residence time in pipeline C (h)[b]	108	29

[a] Biomass yield per gross hectare including allowance for roads, communities, and other nonbiomass land use.

[b] Pipeline slurry velocity is 1.5 m/s *(7,10)*.

[c] From ref. *12*.

[d] From ref. *5*.

cost for any plant size between 2 and 38 dry t/yr of biomass feed. Seven, 13, and 19 circle configurations will have a "close-packed" configuration relative to other plant sizes.

Note that a 38 M dry t/yr ethanol plant would produce at theoretical maximum yield about 300,000 barrels/d (18 billion L/yr) of ethanol. This scale is comparable to the production of transportation fuel from modern large-scale oil refineries. The scale of solids handling would be large in comparison to power generation (a 3 GW coal-fired power plant processes 10–15 M t/yr of coal), but small in comparison to other energy projects (an oil sands plant in Canada producing 250,000 barrels/d of synthetic crude oil processes about 180 M t/yr of bituminous sands).

Two cases were evaluated for treatment at the pipeline inlet. In the low-treatment case, biomass is shredded (stover alone), washed (to remove rock), passed over a magnetic separator to remove iron, then slurried and pipelined at low temperature to the central ethanol plant. In the high-treatment case, biomass is treated the same way, then pretreated with sulfuric acid and neutralized, after which enzymes are added to enable saccharification to take place in the pipeline. This processing sequence is drawn from an NREL design case *(8)*.

Early analysis indicated that the low-treatment case is more economic than the high-treatment case. In the high-treatment case, the cost penalty from many small pretreatment facilities, i.e., one per pipeline inlet, is greater than the benefit realized from saccharification in the pipeline. This is the case even if one assumes that saccharification proceeds to completion within the pipeline, which would eliminate the need for a saccharification tank for all pipelined biomass. In addition, today's enzymatic processes to break down cellulose into glucose require elevated temperature, around 50°C. The cost of heating the slurry going into the pipeline would be prohibitive unless waste heat were available at the pipeline inlet, such as from a power plant *(7)*; note that in an ethanol plant low-quality steam and hot water from the distillation process are available to heat the biomass slurry. Higher-activity enzymes that could catalyze cellulose saccharification at temperatures near 0–20°C would also eliminate the need to heat the slurry.

Cost of Ethanol from Large-Scale Fermentation

Figure 4 compares the calculated cost of ethanol from a large-scale fermentation plant supplied by a combination of truck and pipeline over a range of 4–38 M dry t/yr of biomass with the cost from a truck-supplied plant in a range of 0.73–2 M dry t/yr. Deflections at 14 and 26 M dry t/yr arise from the "close-packing" effect mentioned previously. For corn stover, all plant sizes larger than 2 M dry t/yr supplied by a combination of truck plus pipeline are less economic than the cost of ethanol from plants supplied by truck delivery alone. For wood chips, the cost savings from economy of scale in the processing plant more than offset the rising cost of transportation at a scale of 4–38 M dry t/yr, although the net reduction in ethanol cost with increasing scale is slightly above 14 M dry t/yr.

Pipelining of wood chips benefits from two cost factors compared to corn stover: pipeline lengths are shorter owing to a higher biomass density (yield of biomass per gross hectare), and the pipeline is a smaller diameter (and pumping costs are lower) because the concentration of biomass in the pipeline is higher. We assume a corn stover concentration of 10% DM, which is equivalent to 50% free water because the stover itself reaches a water content of 80%. For wood chips, the concentration is 13% DM (40% concentration of wood chips with a moisture content of 65% water). To assess the relative impact of these two factors, we evaluated one case with

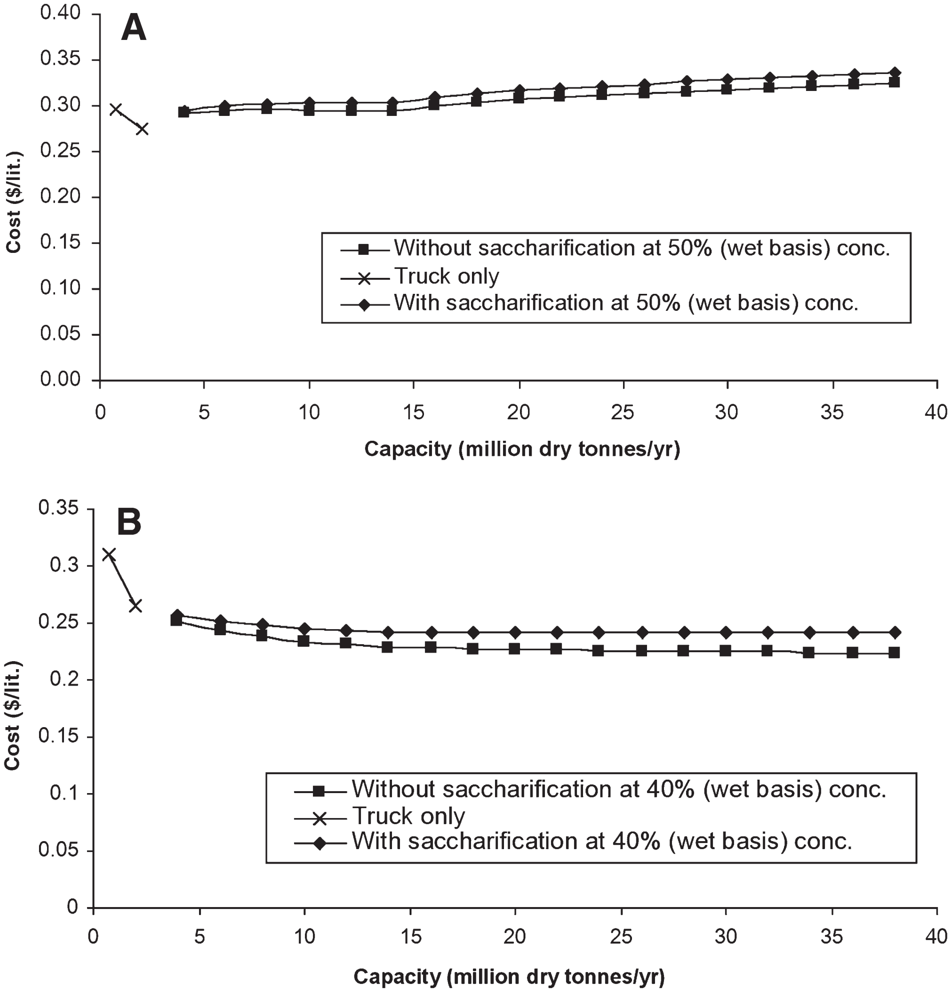

Fig. 4. (A) Cost of ethanol from a corn stover fermentation plant supplied by truck only vs pipeline plus truck; (B) cost of ethanol from a wood chip fermentation plant supplied by truck only vs pipeline plus truck.

a biomass yield of 50% of the base case and a second case with a pipeline concentration of 50% of the base case. The impact of a change in biomass yield on a change in ethanol cost is more than five times greater than the impact of a change in pipeline concentration. Pipeline length is a greater cost driver than pipeline diameter.

Discussion

Figure 4 suggests that for diffuse sources of biomass with low gross yield, such as corn stover, transportation cost overwhelms processing savings as scale increases. For corn stover, the most economic approach to the large-scale production of ethanol would appear to be numerous small plants, with perhaps the only economy of scale being the savings from repeated design and construction of similar facilities. One problem with numerous small processing facilities is that any secondary processing of byproducts would be difficult to conduct at small scale; for instance, chemicals or even energy from lignin is more costly and less efficient in small-scale plants *(11)*.

For higher-density sources of biomass, as illustrated by wood chips, our study indicates that process savings from larger plants more than offset transportation costs, although the incremental impact is relatively small above 14 M dry t/yr. At 14 M dry t/yr, the cost of ethanol is 22.8¢/L, compared with 26.6¢/L for a plant producing 2 M dry t/yr plant supplied by truck alone, a savings of 13%. If a value-added use of a by product such as lignin emerges, then the economics would be even more favorable for a larger-scale plant. It is hard to conceive of a significant processing of chemicals from biomass to arise in numerous distributed small plants, whereas aggregation of biomass in large plants could enable this.

Note, however, that large contiguous areas of high-density biomass are rare in temperate zones and occur primarily in the boreal and tropical forests. Unless large areas of arable land are planted with hybrid tree species, a lower biomass gross density would be more typical of temperate agricultural areas. Also note that in any forested area, energy use of biomass would have to compete with alternate uses of wood fiber for lumber and paper.

A number of simplifying assumptions occur in our study that could be explored in more detail in further analysis. One is that the plant capital and operating cost of fermenting ethanol from biomass does not significantly differ between wood chips and corn stover. If processing of wood chips to ethanol requires more capital than corn stover, then the benefit from larger plants will be even greater. A second simplifying assumption is that transport of biomass in cold water by pipeline without pretreatment does not result in a significant loss of sugar to the carrier fluid (because carrier fluid at the processing plant would be in excess of that needed for fermentation and would presumably be discharged). Treatment of carrier fluid prior to release would likely be by simple impounding, because no chemical treatment of the biomass slurry occurs during pipelining. However, this assumption would require further study in an actual design to ensure that treatment of slurry water in excess of that required in the fermentation plant is not an excessive additional cost. A third simplifying assumption is to model biomass source areas as simple circles, as shown in Fig. 3. Note that the impact of scale on ethanol distribution has not been factored into this study; widespread use of ethanol as a transportation fuel will require a comprehensive distribution system between fermentation plant and fuel retail outlet. One critical issue in comparing pipeline-based larger biomass fermentation plants with distributed smaller plants relying on truck delivery is an accurate identification of the DVC of trucking. The literature contains a fourfold range of this number, from 5 to nearly 20¢/(dry t · km). Three studies of straw and stover based on actual current trucking costs report values near 12.75¢, whereas a theoretical study from ORNL cites 5¢. If the ORNL value is attainable, pipelining of biomass will never be economic.

In this and a previous study, we have used experimental data from wood chip slurries to estimate viscosity and pressure drop in a corn stover pipeline. One critical element of any further study of pipeline delivery of corn stover is a more accurate assessment of viscosity. Keller et al. *(19)* note that treatment of corn stover with phanerochaete results in a major reduction in viscosity. Garcia et al. *(20)* note that sugars in the carrier fluid reduce the viscosity of banana pulp. Hence, future research may identify pretreatment options that can reduce the pumping cost for corn stover.

Conclusion

Truck delivery of biomass to multiple pipeline inlets that deliver biomass as a slurry to a central ethanol fermentation plant offers a means to achieve large plant size while avoiding excessive truck congestion.

For biomass types with a low gross yield per hectare, such as corn stover, the increase in transportation cost is larger than the savings in economy of scale of the fermentation plant. It is more economic to process corn stover in small, distributed fermentation plants supplied by truck. In this case, the sole benefit of economy of scale is the benefit that arises from building numerous identical processing plants.

For biomass types with a higher gross yield per hectare, such as wood chips from the boreal forest, the increase in transportation cost is less than the savings in economy of scale of the fermentation plant and a reduction in the cost of ethanol of more than 10% can be achieved. In addition, a larger fermentation plant would increase the likelihood of processing higher-value products, such as chemicals from lignin.

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