Economies of Size of a Coordinated Biorefinery Feedstock Harvest System

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Abstract

The objective of this research is to determine the cost to harvest lignocellulosic biomass, such as crop residue and perennial grasses, for use as biorefinery feedstock, and to determine the potential economies of size that might result from a coordinated structure. The estimates show that substantial size economies are possible.

Introduction

Agriculture of the 21st century is envisioned to go beyond its traditional role of providing food, feed and fiber to additionally providing the feedstock for biobased resources such as fuels, chemicals, and materials. Goals for the new biobased industry include, increasing domestically produced renewable resources to reduce dependency and vulnerability on petroleum providing nations. A biobased industry would also provide job opportunities in both rural and urban areas and in both the agricultural and industrial sectors (National Agricultural Biotechnology Council). Furthermore, biobased products would emit less pollution than petroleum based products, thus improving air and water quality. Biobased feedstocks are carbon neutral and would not increase atmospheric carbon dioxide, a major contributor to global warming. Also, potential feedstocks, such as native grasses, are generally more environmentally benign than intensive agricultural crops. Chemical inputs are low; there is less disturbance and compaction of the soil, and less risk of soil erosion (Hall and Scrase).

Ethanol, a starch-based form of combustible liquid fuel, is an alternative to and supplement for gasoline. Ethanol can be mixed with gasoline to form “gasohol”, which serves as an oxygenate that enhances combustion thereby reducing emissions. The fermentation-based methods of producing ethanol from corn grain are approaching their inherent theoretical limits.

However, alternative methods of producing ethanol from lignocellulosic biomass (LCB) are being developed.

In laboratory studies it has been demonstrated that LCB may be gasified to produce synthesis gas (composed primarily of CO, CO_2, and H_2). Synthesis gas can be bubbled into a bioreactor and converted by anaerobic bacteria to ethanol and other commodities such as acetic acid and butanol. Gasification-bioconversion technology would permit the use of a variety of potential feedstocks including crop residue, existing perennial native and improved grasses, as well as dedicated energy crops such as switchgrass.

For a conversion ratio of 75 gallons of ethanol per ton of biomass, a conversion facility with a capacity of 100 million gallons per year would require one and one-third million tons of biomass. The logistics of feedstock production, harvest, storage, transport, and delivery could be challenging. For example, Schechinger, who was involved with the management of a pilot corn stover collection project conducted near Harlan, Iowa, has written that the collection, storage, and transportation of a continuous flow of corn stover is a “logistical nightmare”. Furthermore, the harvest machinery and storage facilities would be required to provide a continuous flow of 3,800 dry tons of biomass per day throughout the year to a 100 million gallons per year biorefinery.

Ultimately, the economic viability of a LCB biorefinery will depend in part upon the cost to produce, harvest, and deliver feedstock to the conversion facility. The objective of this research is to determine the cost to harvest LCB, such as crop residue and perennial grasses, for use as biorefinery feedstock, and to determine the potential economies of size that might result from a coordinated structure.

Most prior studies of the cost to harvest biomass have considered only a single feedstock source such as corn stover (Glassner, Hettenhaus, and Schechinger; Gallagher and Johnson; Schechinger) or switchgrass (Walsh; Epplin). Most published biomass harvest cost estimates have been based upon assumptions of a fixed number of acres harvested per year with equipment originally designed to harvest hay. Table 1 includes a summary of biomass harvest cost estimates. These estimates suggest a considerable amount of variability across studies. For example, Gallagher and Johnson estimate a cost of $9 per ton for harvesting corn stover. Cundiff and Harris estimated a cost of $25 per ton to harvest corn stover. Sokhansanj, Shahab and Wright estimate a cost of $18 per ton to harvest switchgrass. One consistent pattern across the studies is that a single point estimate is reported independent of the assumption about the size or number of tons harvested per year by the assumed set of machines.

The present study differs from prior studies in three respects. First, the gasification-bioconversion technology enables the use of a variety of feedstocks, with different maturity dates, enabling a wide harvest window. Second, the long run average cost estimates are generated over a range of size (acres) of operation enabling estimates of economies of size. Third, cost estimates are developed under the assumption of a coordinated set of harvest machines operated by specialized harvest crews.

Data and Method

Harvest windows differ across species enabling the use of harvest and collection machinery throughout many months. Since during harvest months, feedstock could move directly from the field to a biorefinery with limited storage, storage costs would also be reduced. For example, in the southern Great Plains crop residues such as wheat straw may be harvested in June and July, and corn stover in September and October. Harvest of perennial grasses could begin as early as July and continue for an extended period. In the southern Great Plains, switchgrass may be permitted to mature in the field and be harvested as late as February of the following year. A variety of feedstock enables an extended harvest system from June through February of the following year.

In the fall of the year, most perennial grasses translocate nutrients such as nitrogen, phosphorus, and potassium from the above ground plant canopy to the roots. The remaining harvestable above ground plant material is composed mostly of carbon-based lignin and cellulose. Plants mine atmospheric carbon for processing by the biorefinery. In addition to fewer nutrients in the stems, by delaying harvest until nutrients have translocated, biomass tonnage may be decreased, however since the relative amount of carbon in the material is increased, conversion efficiency and combustion quality may be improved. Furthermore, the translocated nutrients stored in the roots can be used for growth and development by the plant year after year, thus reducing the need for and cost of supplementing the soil with nutrients through fertilization. Also, after the nutrients have been translocated, the percent moisture in the stalks and stems is reduced and if rewetted, drying time is also reduced (Hadders and Olsson). Delayed harvest also reduces the need for storage. Feedstock may be stored uncut in the field until it is needed.

Seasonality of the biomass growth must also be considered when determining scheduling of harvest. The costs of producing and harvesting nearly year-round with multiple harvest-equipment units for abundant biomass acreage may be less costly than farm-sized haymaking techniques due to the economies of size. This is similar to cost efficiencies obtained by custom crop harvesters that harvest wheat and other grain crops in the Great Plains (Kastens and Dhuyvetter). Crews with several combines, trucks, trailers, and laborers begin harvesting in regions where the crops mature first and migrate as the harvest season progresses. For example, wheat harvest crews begin harvesting wheat in Texas in May and travel north as the crop matures eventually into Canada. Use of a variety of perennial species with different maturity patterns would enable similar cost savings for a gasification-bioconversion biorefinery.

It is assumed that harvest crews would develop in concert with a LCB feedstock biorefinery industry. These may be organized as a coordinated function of a biorefinery or as independent contractors. In the Southern Plains, with a variety of feedstocks, harvest could begin as early as June and continue through February of the following year. The acres required for the harvest of specified amounts of feedstock required by a biorefinery depend on the yield of biomass. Table 2 includes estimates of the acres needed for different biomass quantity requirements based on annual per acre yields.

Two software programs, AGMACH$ (Huhnke) and MACHSEL (Kletke and Sestak), were used to generate the cost estimates. Both programs use the machinery cost equations published in the American Society of Agricultural Engineering Handbook and the American Agricultural Economics Association Costs and Returns Handbook including repair factor coefficients and remaining value coefficients. These estimation procedures were used to estimate ownership costs including depreciation, interest on average investment, insurance and taxes, and operating costs including fuel, oil, lubricants, and repairs. Some of the equations used in these programs are included in the Appendix.

It was assumed that LCB harvest and field storage would require machines that could mow, rake, and bale LCB and a machine that could collect, transport, and stack bales at a location near an all weather road. It was also assumed that the search for machines would be limited to established technology and available agricultural equipment. Finally, the search for machines was limited to equipment that could travel quickly and legally on section line county roads and highways.

A three-step procedure was used. First, AGMACH$ was used to determine which specific type of mower, rake, and baler would result in the lowest costs at intensive levels of use. Second, MACHSEL was used to design a coordinated set of machines. Third, the number of acres to be harvested was parameterized to enable determination of an estimate of the long run average cost curve for alternative biomass yields.

It was determined that two 10-foot rotary mowers (mower conditioner) pulled by a 95 horsepower tractor would be the least-cost method of cutting. The mowers are designed and constructed to be operated in tandem. Two rotary mowers can be arranged to mow one 20-foot windrow or two 10-foot windrows simultaneously. A specially designed tandem hitch enables the two mowers to operate at a field width of 20 feet. However, for transport, the second mower may be aligned to pull behind the tractor for a transport width of 10 feet.

It was also determine via AGMACH$ that two 10-foot rakes also operated in tandem and pulled by a 95 horsepower tractor would be the least-cost method of raking. AGMACH$ also enabled the comparison of costs of balers that form small, medium, and large size bales. For large volumes of material, it was determined that balers that form large rectangular solid (approximately 4 feet by 4 feet by 8 feet) bales would be the least-cost method of baling. A 150 horsepower tractor would be required to pull these machines.

A bale transporter may be used to acquire and stack bales in the field or at a location within 10 miles. Self-propelled bale transporters that can travel in a field and collect as many as eight large rectangular solid bales, transport them and stack them adjacent to an all weather road are commercially available (Matlack). One was selected for budgeting. List prices and estimated hours of life for these machines are reported in Table 3. Table 4 includes the budgeted operating speeds for alternative yields and windrow widths, for mowers, rakes, balers, and bale transporters.

The MACHSEL program was used to build a coordinated set of machines. The program was used in an iterative fashion to match machines and to build a set of machines for a harvest crew. It was determined that a coordinated set of harvest machines includes: three 150 horsepower tractors; three balers; six 95 horsepower tractors; three sets of tandem 10-foot rotary mowers; three sets of tandem 10-foot rakes; and one bale transporter. The raking occurs at the same speed or faster than both the mowing and the baling. The mowing occurs at the same speed or faster than the baling. However, it is assumed that the bale transport unit will operate at approximately three times the speed of the baler.

Table 5 includes estimates of the daily harvest capacity in terms of acres for a harvest unit (three sets of tandem mowers, three rakes, three balers, and one transporter) for alternative species and alternative machine hours per day. Note that for native prairie, miscellaneous feedstock (improved perennials such as Bermudagrass, fescue, and old world bluestem), and wheat straw, the coordinated set of machines; three sets of tandem mowers, three sets of tandem rakes, three balers, and one transporter have the same daily capacity. For switchgrass, higher yields are assumed such that three sets of tandem mowers would have twice the daily capacity of three balers. If the yields are greater than four tons per acre, the mower covers the area in relatively half the time as the baler. This results from the mower’s ability to simultaneously mow two ten-foot swaths while the baler can only bale one at a time.

Results and Conclusions

Figure 1 contains a chart of the estimated costs to harvest a ton of biomass as a function of the number of acres harvested annually. This is the long run average cost of machinery ownership and operation. The chart shows the magnitude of the potential economies of size expected from a coordinated harvest system. For a relatively low yielding feedstock, such as two tons per acre, the lowest costs of $4.96 per ton were achieved at a harvest unit capacity of 100,000 acres per year. Recall that the harvest unit includes three 150 horsepower tractors; three balers; six 95 horsepower tractors; three sets of tandem mowers; three sets of tandem rakes; and one bale transporter and the personnel required to operate the machines. For a relatively high yielding feedstock such as six tons per acre, the lowest cost of $3.84 per ton were achieved at a harvest unit capacity of approximately 30,000 acres. Based upon the estimates reported in Table 5 for miscellaneous feedstocks such as Bermudagrass, fescue, and old world bluestem, a harvest unit has an estimated capacity of approximately 230 acres in an eight-hour day. If the unit operated an average of 20 field days per month for nine months, the unit capacity would be approximately 41,000 acres (17,000 hectares) per year.

The lowest total costs in the figure are $3.84 per ton for yields of six tons per acre, $3.54 per ton for five tons per acre, $4.28 per ton for four tons per acre, $4.14 per ton for three tons per acre and $4.96 per ton for yields of two tons per acre. These costs to cut, rake, bale, and transport from the field to a storage site near an all weather road of approximately $4 to $5 per ton are substantially lower than previous estimates of the cost to harvest LCB biomass.

This study has several limitations and shortcomings. First, the analysis was limited to machines that are designed, manufactured, and sold for the purpose of harvesting forage for use as livestock feed. More specialized and cost efficient machines may be designed to accommodate a LCB feedstock industry. Second, the functions used to estimate the machinery operating and ownership costs were based upon farm rather than industrial use levels and conditions. Third, the estimates are contingent upon the assumption that a biorefinery could efficiently use a variety of feedstocks. Fourth, it is assumed that harvest crews that are employees of the biorefinery with equipment that may be wholly owned by the biorefinery would be permitted. Institutional constraints (local, state, or federal legislation) could be imposed that would restrict the business ties between feedstock harvesting and feedstock processing.

Research is necessary to address a number of remaining issues and questions. For example, additional work will be required to determine if gasification-bioconversion can compete with conventional refining. Additional research is also necessary to determine the carbon yields and nutrient content by month of harvest for each of the potential feedstocks. Work is also necessary to determine if the yields of the potential feedstocks can be maintained over time.

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Appendix

The quantity of acres processed by a specific machine is calculated by, equation 1, multiplying the speed of travel by the width of the implement by the efficiency to get acres worked per hour. The number of hours worked by the equipment is assumed to be 10% less than the number of hours required by the tractor, which is also assumed to be 10% less than the number of labor hours required for the activity. Table 5 includes estimates of actual harvest working time based on an 80% efficiency level and 8, 10, and 12 hour work days.

$$(1) \quad \frac{Speed(miles/hour) \times Width(feet) \times Efficiency(\%)}{8.25(feet \times miles/acres)} = \frac{Acres}{Machine\ Hour}$$

$$(2) \quad \frac{LaborHours}{1.1} = TractorHours$$

$$(3) \quad \frac{TractorHours}{1.1} = MachineHours$$

MACHSEL was modified by changing the salvage value and repair cost equations to the remaining value and accumulated repair cost equations found in the American Society of Agricultural Engineering Handbook (2001) with updated coefficients.

$$(4) \quad Remaining\ Value_n = LP * [C_1 - C_2(n^{0.5}) - C_3(h^{0.5})]^2$$

where: LP = machine list price (\$); C_1 , C_2 and C_3 are parameters; n = expected life (years); and h = expected hours of life (hours).

$$(5) \quad Annual\ Repair\ Cost = \frac{LP * RF1 * (TH/1000)^{RF2}}{Years}$$

where: *RF1* and *RF2* parameters; *TH* = total expected hours of use; *Years* = expected life (years).

Table 1. Published Estimates of Biomass Harvest Cost

Author(s)	Year	Feedstock(s)	Yield(s) Assumed	Types of Machines	Tasks Considered	Mow Rake Bale Store Transport	Estimated Cost to Deliver $/Mg
English, Short and Heady	1981					Farm Level Costs $12.88/Mg	6.4 Km $0.84 16.1 Km $1.05 24.1 Km $1.16 32.2 Km $1.32 48.3 Km $1.65 80.5 Km $2.21
Cundiff and Harris	1995			Mow-Conditioner, Rake, Large Round Baler	Loader and three trucks for trans. 65 Km round trip	$27.56/dMg	$2.98/dMg, Load $10.69/dMg, Haul 64.36 Km
Epplin	1996	Switchgrass	7 Mg/ha 9 Mg/ha 11 Mg/ha				$14.98/Mg $11.91/Mg $6.73/Mg
Glassner, Hettenhaus and Schechinger.	1998	Corn Stover	3.4-4.5 Mg/ha			$34.79-$39.30/Mg	
Walsh	1998	Switchgrass	11.2 Mg/ha				$5.65/Mg
Gallagher and Johnson	1999	Corn Stover	6 Mg/ha	Large Round Balers	Cut and Chop with Combine	Chopping $2.20/Mg Baling $6.87/Mg Farm Tran $1.15/Mg	
Nienow, McNamara, Gillespie, and Preckel	1999	Woody Biomass	40.3-54 Mg/ha		Harvester Service Field Trans.	$49/Mg $19.75/Ha	
Schechinger	2002	Corn Stover		Large Round Balers Large Square Balers	Combining, Raking, Windrowing, and Baling	~$16.5/d, Round Bales >$22/dMg, Large Sq. Bales	
Sokhansanj, Shahab and Wright	2002			Mower Cond. Rake Baler Sq. Stacker Telescopic handler	10 Hour Working days for 45 days per year 7 Hour Working days for 200 days.	Mow. $1.06/dMg Rake $0.43/dMg Bale $7.34/dMg Stack $9.50/dMg Handle $1.47/dMg	

Table 2. Number of Harvested Acres Required to Provide Feedstock for Biorefineries of Alternative Capacities for Feedstock Yields of Two to Six Dry Tons per Acre

Biomass (million tons/year)	Yield Per Acres (tons)				
	2	3	4	5	6
1.50	750,000	500,000	375,000	300,000	250,000
1.33	665,000	443,333	332,500	266,000	221,667
1.25	625,000	416,667	312,500	250,000	208,333
1.00	500,000	333,333	250,000	200,000	166,667
0.75	375,000	250,000	187,500	150,000	125,000
0.66	330,000	220,000	165,000	132,000	110,000
0.50	250,000	166,667	125,000	100,000	83,333
0.33	165,000	110,000	82,500	66,000	55,000
0.25	125,000	83,333	62,500	50,000	41,667

Table 3. List price and Estimated Hours of Life for Selected Machines

Unit	Price	Hours of Life
95 hp Tractor	$ 44,300	10,000
155 hp Tractor	$ 63,200	10,000
Rotary Mower	$ 20,000	2,500
Rake, Twin Wheel	$ 6,000	2,500
Baler	$ 67,000	3,000
Bale Transporter	$115,000	10,000

Table 4. Budgeted Operating Speeds for Alternative Yields and Windrow Widths, for Mowers, Rakes, Balers, and Bale Transporters.

Yield (tons/acre)	Windrow Width (feet)	Speed (miles per hour)			
		Mower	Rake	Baler	Bale Transp.
0.5	20	7.0	7.0	7.0	21.0
1.0	20	7.0	7.0	7.0	21.0
1.5	20	6.5	7.0	6.5	19.5
2.0	20	6.0	7.0	6.0	18.0
2.5	20	5.5	6.5	5.5	15.7
3.0	20	5.0	6.0	4.5	13.5
3.5	20	4.5	5.5	3.7	11.2
4.0	20	4.0	5.0	3.0	9.0
4.5	10	5.0		5.0	15.0
5.0	10	4.5		4.5	13.5
5.5	10	4.0		4.0	12.0
6.0	10	3.5		3.5	10.5

Table 5. Daily Harvest Capacity in Terms of Acres for a Harvest Unit (Three Mowers, Three Rakes, Three Balers, and One Transporter) for Alternative Species and Alternative Machine Hours per Day

	Width	Speed	Machine	Daily Labor Hours per Operation					
Operation	(feet)	(miles/hour)	acres/hour	8	10	12	16	18	20
Switchgrass									
Mowers (3)	20	3.5	20.36	135	168	202	269	303	337
Rakes (3)	20	3.5	20.36	135	168	202	269	303	337
Balers (3)	10	3.5	10.18	67	84	101	135	152	168
Transporter	10	10.5	10.18	67	84	101	135	152	168
Native Prairie									
Mowers (3)	20	5.25	30.55	202	252	303	404	454	505
Rakes (3)	20	5.25	30.55	202	252	303	404	454	505
Balers (3)	20	5.25	30.55	202	252	303	404	454	505
Transporter	20	15.75	30.55	202	252	303	404	454	505
Miscellaneous Feedstock									
Mowers (3)	20	6	34.91	231	289	346	462	519	577
Rakes (3)	20	6	34.91	231	289	346	462	519	577
Balers (3)	20	6	34.91	231	289	346	462	519	577
Transporter	20	18	34.91	231	289	346	462	519	577
Wheat Straw									
Mowers (3)	20	7	40.73	269	337	404	539	606	673
Rakes (3)	20	7	40.73	269	337	404	539	606	673
Balers (3)	20	7	40.73	269	337	404	539	606	673
Transporter	20	21	40.73	269	337	404	539	606	673

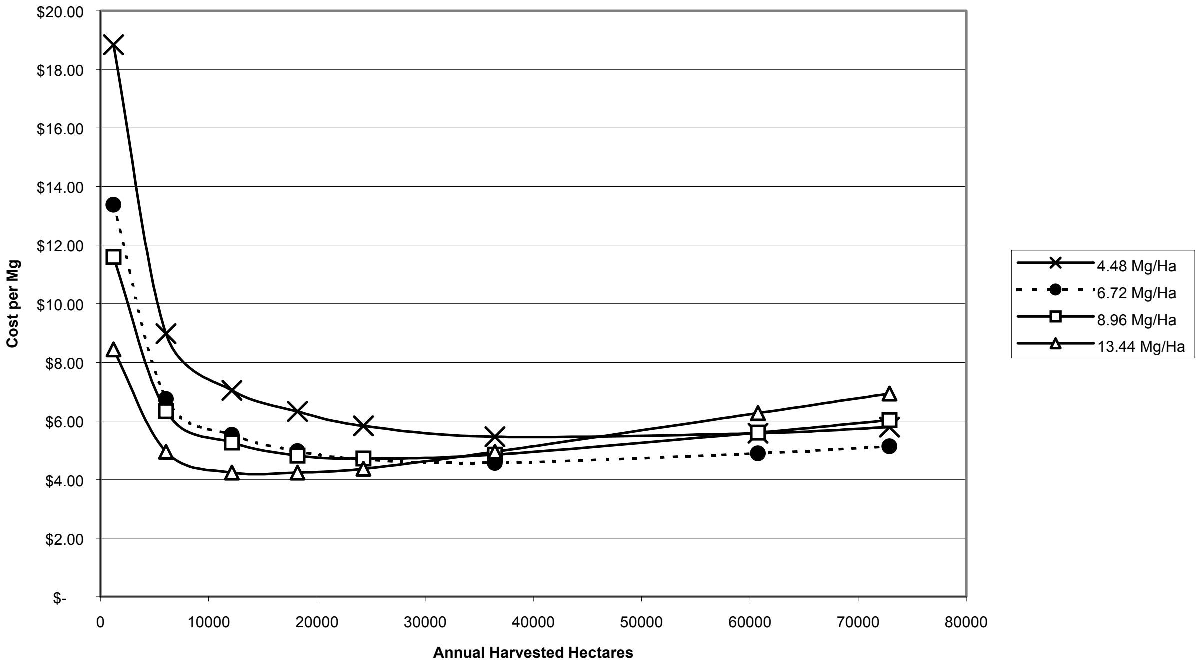

Figure 1. Long Run Average Harvest Costs per Mg of Biomass for Yields of 4.48, 6.72, 8.96, and 13.44 Mg/Ha (2, 3, 4, and 6 tons per acre) for Annual Harvest from Zero to 70,000 hectares (0 to 173,000 acres).