Net energy output from harvesting small-diameter trees using a mechanized system

Fei Pan*
Han-Sup Han*
Leonard R. Johnson*
William J. Elliot

Abstract

What amount of extra energy can be generated after subtracting the total energy consumed to produce the biomass energy? Knowing the ratio between energy output and input is a valid question when highly mechanized systems that consume fossil fuels are used to harvest and transport forest biomass for energy. We estimated the net energy generated from mechanical fuel reduction thinning treatments on pure ponderosa pine stands in Arizona. The mechanized system (felling, skidding, loading, grinding, and hauling) was monitored for energy consumption. Potential energy output from harvested forest biomass was calculated based on hog fuel moisture content and heating value. A 9-day study showed positive net energy output of 3,471,376,292 BTUs. The net energy ratio between energy output and input was 10.41, and the energy cost from stump to energy plant was \$4.65/million BTUs. Energy used for hauling hog fuel represented the largest part (36.27%) of the total energy input. The net energy ratio decreased 0.11 with each additional transportation mile. Energy cost increased by \$0.04/million BTUs, \$0.13/million BTUs, and \$1.48/million BTUs for each additional mile of highway, unpaved road, and spur road, respectively. A one dollar per gallon diesel price increase added \$0.34/million BTUs to the energy cost. Forest biomass energy has an encouraging net energy ratio compared with other biomass sources, but the high production cost and energy cost can impede the use of forest biomass for energy.

Rising fuel costs and the scarcity of fossil fuels have renewed interest in the use of wood fuel in the United States (Arola and Miyata 1980). Traditional forest and mill residues received considerable attention as supplements to conventional fossil fuels during the energy crisis in the early 1970s (Arola and Miyata 1980), and the use of forest and agricultural residues in direct-combustion systems for power and heat generation has been a well-established practice in the forest products industry (Han et al. 2002). Today, biomass sources provide 3 percent of all energy consumed in the United States, while supplying about half of all renewable energy generated in the country (Perlack et al. 2005).

In the past 50 years, successful fire suppression in the nation's forest resulted in a dense understory throughout the forests (Han et al. 2002). These overstocked small-diameter stands generally require thinning from below to improve fire-tolerance and restore them to historical conditions (Graham et al. 2002). To ensure that a thinning operation reduces fire risk for the residual stand, the operation must either remove submerchantable trees and logging slash completely through biomass harvesting or carefully burn the fuels using a prescribed fire (Han et al. 2002). Using these small-diameter trees in addition to traditional logging residue for power

The authors are, respectively, Graduate Research Assistant, Dept. of Forest Products, Univ. of Idaho, Moscow, Idaho (feipan@vandals.uidaho.edu); Associate Professor, Dept. of Forestry and Wildland Resources, Humboldt State Univ., Arcata, California (hh30@humboldt.edu); Professor, Dept. of Forest Products, Univ. of Idaho, Moscow, Idaho (ljohnson@uidaho.edu); and Team Leader, USDA Forest Serv., Rocky Mountain Research Sta., Moscow, Idaho (welliot@fs.efed.us). This study was funded by a grant from the National Fire Plan through the USDA Forest Serv., Rocky Mountain Research Sta. The cooperation of USDA Forest Serv. at Apache-Sitgreaves National Forest and Walker Brothers Logging made this study possible. This paper was received for publication in June 2007. Article No. 10377.
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generation creates an additional opportunity for forest biomass energy (Morris 1999, Bolding 2002).

Mechanical harvesting, processing small-diameter trees, and transporting hog fuel for energy are often cost-prohibitive and associated with questions about the net energy contribution of the process. Adams (1983) reported net energy ratios from 18.2 to 25.0 for harvesting (without transportation) stems 4 to 8 inches in diameter and 4 to 10 feet in length (mixed species) using a cable system. However, the literature lacks well-documented information on the net energy output when using ground-based systems to harvest small-diameter ponderosa trees for energy.

Table 1. — Production time and energy consumed to harvest forest biomass for the 9-day operation.

	Feller-buncher	Skidder	Loader	Grinder	Chip van
Horsepower (hp)	130	160	130	500	400
Total production time (hr)	49.33	32.72	30.05	29.80	88.92
Total diesel used (gal)	294.9	165.5	80.2	519.9	977.0
Diesel use per BDT[a] biomass (gal/BDT)	0.83	0.46	0.23	1.46	2.75
Diesel consumption rate (gal/hr/hp)	0.046	0.032	0.021	0.035	0.027
Utilization rate (%)[b]	88.1	66.1	61.5	60.8	78.3

[a]BDT: bone dry ton.
[b]Utilization rate (%) = (productive machine hour / scheduled machine hour) × 100.

A net energy analysis was performed to investigate the net energy output of harvesting, processing, and transporting small (diameter at breast height, DBH $\leq$ 5.0 inches) ponderosa pine trees for energy. The operations were directly associated with a fuel reduction thinning treatment. Net energy analysis is a technique that seeks to compare the amount of energy delivered to society by a technology with the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form (Cleveland and Costanza 2006).

The study objectives were: 1) to examine the total fossil fuel consumption and biomass energy production, 2) to determine the net energy ratio between biomass energy output and fossil energy input, and 3) to test the effects of different variables on the net energy ratio and energy cost. These variables included hauling distance at various road standards and diesel prices.

Methodology

Study sites and harvesting system

The two study sites were located in Springerville and Black Mesa, Arizona, stocked with nearly 100 percent ponderosa pine (*Pinus ponderosa*) trees. The silvicultural prescription required all the trees less than or equal to 5.0 inches in DBH to be removed and all the trees greater than 5.0 inches in DBH to be reserved. A mechanized whole-tree system (**Table 1**) was used to harvest the trees. A three-wheel hot-saw feller-buncher (Valmet 603) felled and bunched trees prior to skidding them to a landing using a rubber-tired grapple skidder (CAT 525B). A stationary log loader (Prentice RT-100) at the landing fed the whole trees into a remote-controlled horizontal grinder (Bandit Beast 3680). The processed hog fuel was loaded directly into a chip van through the grinder's conveyor. Chip vans that could be hooked or disconnected from the truck were used for landing-to-market hauling. The hog fuel was sent to two local energy plants. The one-way hauling distance to each plant ranged from 29.5 to 36 miles (**Table 2**).

Table 2. — Hauling distance and average speed for various road standards.

	One-way distance in miles				
	Spur[b]	Unpaved[c]	Paved[d]	Highway[e]	Total
Unit 1	1.5	8	2.5	17.5	29.5
Unit 2	0	10.5	1	22.5	34
Unit 3	0	0	0	35	35
Unit 4	0	0	0	36	36
Average speed (miles/hour)[a]	2.67	13.83	14.40	44.14	--

[a]The average speed was calculated using the road distance divided by the time traveling on it. The two-sample t-test did not find significant speed difference between travel loaded and travel empty ($p = 0.062$, $\alpha = 0.05$).
[b]Spur road: one lane forest road without gravel top or pavement.
[c]Unpaved road: one-lane, graveled forest road.
[d]Paved road: one-lane road with pavement, connects highway and unpaved road.
[e]Highway: two-lane state highway.

Energy input

In this study, direct energy consumption consisted of fuel consumed for harvesting, processing small trees, and transporting the hog fuel. The amounts of diesel used by the feller-buncher, skidder, loader, and grinder were measured by an electronic fuel meter installed on the fueling gun. Readings on the electronic fuel meter were recorded each time machine fuel tanks were filled, with specific recordings before operations started and after operations ended in each unit. Truck diesel consumption was recorded by the driver for each harvesting site. The reported average truck diesel consumption rate of 0.4 gallon per mile was applied for the entire transportation network, as it was impossible to segregate diesel consumption rate for different road types.

This study did not directly measure the indirect energy input that was required for moving equipment and for crew transportation. Fuel consumption in moving equipment was assumed to have the same diesel consumption rate as for hog fuel hauling because they both used trucks for transportation. Energy used for moving machines away from the site was not considered for this study as this is typically assigned to the following project. Fuel consumed by pickup trucks for crew transportation was measured by the operator for each harvesting site. Fuels spent for chain saw operation and administration were not included.

The summed direct and indirect diesel consumption amounts were converted to an equivalent heating value (British thermal unit, BTU) as the total energy input. The energy content was taken at 137,000 BTUs per gallon for diesel, and 125,000 BTUs per gallon for gasoline (Adams 1983). Other energy inputs, such as energy consumed for active drying, storage, and energy conversion, were not considered because they appear in the hog fuel markets (energy plants) and are outside the scale for this production study.

Table 3. — Direct diesel consumption for the 9-day operation.

		Feller-buncher	Skidder	Loader	Grinder	Chip van	Total
Direct diesel input (gallons)	Unit 1	44.4	27.5	16.6	93.3	148.0	329.8
	Unit 2	38.2	26.0	10.8	64.5	185.0	324.5
	Unit 3	145.8	88.1	39.8	276.1	483.0	1032.8
	Unit 4	66.5	23.9	13.0	86.0	161.0	350.4
	Total	294.9	165.5	80.2	519.9	977.0	2037.5
Heating value[b] (BTUs[a])		40,401,300	22,673,500	10,987,400	71,226,300	133,849,000	279,137,500
Average consumption (gal/hr)		5.98	5.06	2.67	17.45	10.99	42.15
Percent total		14.47	8.1	3.94	25.52	47.95	100

[a]BTUs: British thermal unit.
[b]Based on 137,000 BTUs per gallon of diesel (Adams 1983).

Energy output

Energy output was defined as the total recoverable heating value from the produced hog fuel and was calculated using the following formula (Ince 1979):

$$RHV = HHV \cdot (1 - MC_{wb}) - HL \qquad [1]$$

where:

RHV = recoverable heating value, BTUs/pound
HHV = higher heating value, or the maximum potential energy in dry hog fuel, BTUs/pound
MC_{wb} = wet-based moisture content, percent
HL = heat loss, BTUs/pound

Two random hog fuel samples were collected from each truckload to evaluate their higher heating value (HHV). All the samples from the 32 truckloads were taken to the University of Idaho Forest Products Department lab to measure the HHV using an oxygen bomb calorimeter following the standard described by the American Society for Testing and Materials E 711–87 (ASTM 2003a). In addition, one sample was randomly selected for each cutting unit to determine the HHV testing times. These four samples were each measured for the HHV 12 times to provide a good sample size for the variance detection. One-way ANOVA analysis was performed to detect the variance between the samples and to compare the mean HHV of each sample.

Heat loss was estimated under the following assumptions (Ince 1979): the combustion heat recovery system was operated with 40 percent excess air and a stack gas temperature of 260 °C, which is typical for an industrial system; the ambient temperature of hog fuel before combustion (room temperature) was 20 °C; the constant conventional heat loss factor was 4 percent and the hog fuel had complete combustion.

The total hog fuel green weight was tracked from the scaling ticket information of the energy plant tickets during the operation. Hog fuel samples' moisture contents (MC) were measured at the Forest Energy Corp., Arizona, during the study using an AND Infrared Moisture Determination Balance AD-4712. MC measurements following the American Society of Testing and Materials E 871–82 guidelines (ASTM 2003b) were conducted in the University of Idaho lab after the field study ended. Each sample was measured for the MC three times, and the average value was applied in the calculation. A paired two-sample t-test was used to test the MC difference between Arizona and Idaho experiments.

Sensitivity analysis

After initial analysis on net energy ratio (energy output/energy input) and energy cost ($/million BTUs), sensitivity analyses were performed to test the effect of hauling distance on net energy ratio and energy cost, and the effect of diesel price on energy cost. To test the effect of hauling distance on the net energy ratio, different one-way distances were simulated to estimate the corresponding energy input. The net energy ratio change could be found given a constant energy output. The impact of travel distance on energy cost was detected by setting distinct highway, unpaved road, and spur road distances in a developed hauling cycle time regression model while keeping all the other variables constant (Pan et al. 2007). The resulting value change in cycle time was then converted to a production cost ($/bone dry ton, or $/BDT) change. Combining the constant energy output with the production cost change, the energy cost change could be calculated. The diesel price influence on the energy cost was determined by assuming different diesel prices. The resulting production cost change was then transformed to the corresponding energy cost change. Scatter plots showed how the net energy ratio and the energy cost changed with the corresponding value change in the test variables.

Results

Energy input

The total direct diesel consumption was 2037.5 gallons for the harvesting system, equivalent to 279,137,500 BTUs (**Table 3**). Truck hauling was the largest direct energy input component (47.95%) because it had the longest operation time with a relatively high-horsepower engine. The skidder, loader, and grinder worked as a "hot" system, meaning they had similar production times. The grinder consumed 25.52 percent of the total direct input energy, reflecting the large engine size (500 horsepower) of the machine and the highest diesel consumption rate (gal/hr/hp, **Table 1**) in the hot system. Although the loader had an engine similar in horsepower to the skidder, it had a lower diesel consumption rate than the skidder, resulting in less diesel use. The feller-buncher worked independently and consumed 14.47 percent of the direct input energy due to long working time and the highest diesel consumption rate.

The total indirect energy input was 667.8 gallons of diesel and gasoline, equal to 89,868,600 BTUs (**Table 4**). The diesel used for moving machines accounted for 60.64 percent of the total indirect energy input. The pickup trucks for crew transportation expended 39.36 percent of the indirect energy input.

Table 4. — Indirect fuel consumption for the 9-day operation.

	Machine moving	Crew transportation		
	Diesel	Diesel	Gasoline	Total
Site 1	122.4	27	27	176.4
Site 2	275.4	108	108	491.4
Total	397.8	135	135	667.8
Average (gal/day)	44.2	15	15	74.2
Total heating value (BTUs)[a]	54,498,600	18,495,000	16,875,000	89,868,600
Percent total[b]	60.64	20.58	18.78	100

[a]Based on 137,000 BTUs per gallon of diesel and 125,000 BTUs per gallon of gasoline (Adams 1983).
[b]Equivalent heating value indicated in percent of the total consumption.

Table 5. — Total input fuel amounts and the equivalent heating values.

	Direct energy input	Indirect energy input	Total
Diesel and gas amount (gal)	2,037.5	667.8	2,705.3
Equivalent heating value (BTUs)	279,137,500	89,868,600	369,006,100
Percent total[a]	75.65	24.35	100

[a]Equivalent heating value indicated in percent of the total consumption.

Table 6. — Higher heating values (HHV) for the four hog fuel samples. The HHV for each sample was measured for 12 times.

	Hog fuel sample source	Higher heating value in BTUs/pound	
		Mean	S.D.
Sample 1	Unit 1	9,070	30.1
Sample 2	Unit 2	8,992	31.1
Sample 3	Unit 3	8,946	43.2
Sample 4	Unit 4	9,105	27.1

Table 7. — ANOVA source table for detecting the hog fuel higher heating value difference.

	S.S.[a]	D.F.[b]	M.S.[c]	F[d]	*p*-value
Between	189,440	3	63,145	56.51	0.0000
Within	49,167	44	1,117.4		
Total	238,600	47	5,076.7		

[a]S.S.—sum of squares.
[b]D.F.—degrees of freedom.
[c]M.S.—mean squares.
[d]F = M.S. (between) / M.S. (within)

Table 8. — Hog fuel MC and heating values by biomass harvesting units.

	Tree DBH (inches)	Average MC (green basis, %)	Higher heating value (BTUs/pound)	Recoverable heating value (BTUs/pound)
Unit 1	5.11	55.66	9,070	2,459
Unit 2	5.41	53.25	9,076	2,663
Unit 3	1.76	50.02	9,041	2,917
Unit 4	1.91	52.06	9,064	2,758
Average	3.55	52.75	9,063	2,699

This percentage was high because the crew traveled about 100 miles (one-way) to site 2 each day.

The total energy input (**Table 5**) for the 9-day operation was 2705.3 gallons of fossil fuel. The total fuel input had an equivalent heating value of 369,006,100 BTUs. The direct and indirect energy consumption represented 75.65 percent and 24.35 percent of the total energy input, respectively, in terms of equivalent heating value. Hog fuel hauling represented the largest part of direct energy input with 36.27 percent of the total energy input, while machine transportation, the largest part of indirect energy input, consumed 14.77 percent of the total input energy.

Energy output

The descriptive statistics for the lab-derived hog fuel HHV (**Table 6**) showed that the mean HHV ranged from 8,946 to 9,105 BTUs/pound and the SD varied from 27.1 to 43.2 within each hog fuel sample, which was less than 1 percent of the mean HHV. This indicated that one experiment was sufficient for the rest of the samples instead of multireplication. The one-way ANOVA analysis (**Table 7**) provided an F-value of 56.51 with a p-value less than 0.00001 ($\alpha = 0.05$), indicating that the mean HHV of the four hog fuel samples had a significant difference. The experiments showed that hog fuel HHV ranged from 8,885 to 9,273 BTUs/pound with an average value of 9,063 BTUs/pound. The hog fuel from unit 3 had the lowest average HHV of 9,041 BTUs/pound (**Table 8**). Ponderosa pine bark has higher HHV than the wood on a weight basis (Ince 1979). The preharvest cruise found the trees in unit 3 had the smallest DBH (Pan et al. 2007), indicating the lowest bark thickness and weight percentage (Johnson 1956).

The paired two-sample t-test found the moisture tests between Arizona and Idaho experiments had no significant difference ($p = 0.068$, $\alpha = 0.05$). Idaho experiments showed that the average hog fuel MC varied by cutting units from 50.02 percent to 55.66 percent, with an average value of 52.75 percent (**Table 8**). The operation lasted from late July to early August, when monsoon rains saturated the fuel. The operation in unit 3 did not encounter rainfall and produced the driest hog fuel of the four units.

The average heat losses due to MC, hydrogen, dry gas and excess air, and conventional factor were 657.5, 318.0, 436.0, and 171.3 BTUs/pound, respectively. The total average heat loss was 1,582.8 BTUs/pound. By applying Equation [**1**], the recoverable heating value of the hog fuel was determined to be 2,699.4 BTUs/pound. Despite having the lowest HHV, the hog fuel from unit 3 had the highest recoverable heating value of 2,917 BTUs/pound because it had the lowest MC (**Table 8**). Keeping the rain from soaking the wood is critical to ensure a high recoverable heating value.

For this study, total hog fuel production was 711.34 green tons at MC of 52.75 percent, or 336.11 bone dry tons. The total recoverable energy output was 3,840,382,392 BTUs. Subtracting the energy input, the net energy output was determined to be 3,471,376,292 BTUs. The net energy ratio between the recoverable energy output and the fossil energy input was 10.41:1.

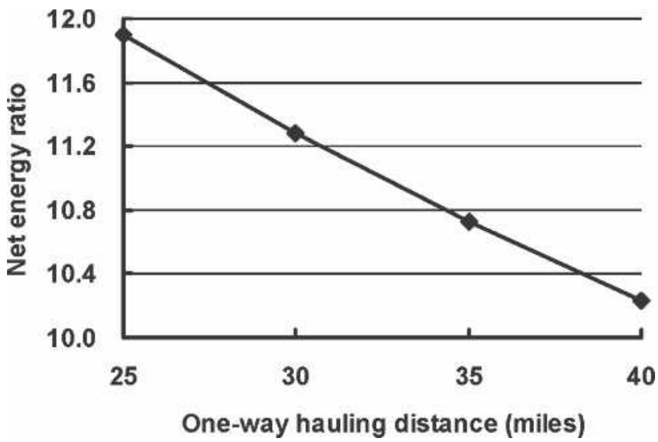

Figure 1. — Effect of one-way hauling distance on net energy ratio.

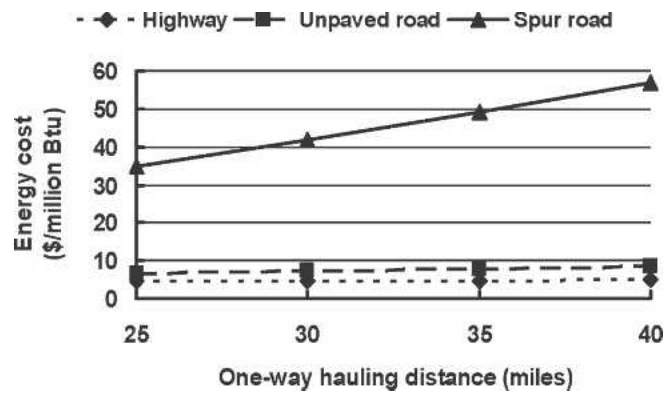

Figure 2. — Effect of one-way hauling distance of various road types on biomass energy cost.

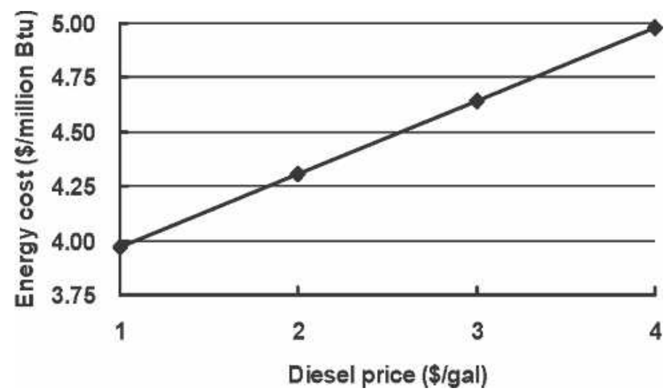

Figure 3. — Effect of diesel price on biomass energy cost.

Sensitivity analysis

Based on the diesel consumption rate of 0.4 gallon per mile, energy used for hauling was tested by setting the one-way distance to 25, 30, 35, and 40 miles. Sensitivity analysis showed a negative relationship between the hauling distance and the net energy ratio (**Fig. 1**). For the distances from 25 to 40 miles, the net energy ratio varied from 11.90 to 10.23. Each mile of hauling distance increase decreased the net energy ratio by 0.11 on average.

A time study that accompanied this analysis (Pan et al. 2007) generated the following regression function for the hauling cycle time (from loading hog fuel at the landing to traveling empty back to the landing) with all the variables significant:

Hauling cycle time (min) = 26.2300
+ 0.0014 (Hog fuel green weight, pound)
+ 2.3158 (one-way highway distance in miles)
+ 8.4910 (one-way unpaved road distance in miles)
+ 107.1160 (one-way spur road distance in miles).

$$(\alpha = 0.05, p < 0.00001, r^2 = 0.98)$$

The production cost study found an overall cost of $53.15/BDT for harvesting, processing, and transporting the hog fuel (Pan et al. 2007). Combining this with the recoverable heating value of 3,840,382,392 BTUs for 336.11 BDTs of hog fuel, an energy cost of $4.65/million BTUs resulted. Setting one-way highway distance to 25, 30, 35, and 40 miles varied the energy cost from $4.45/million BTUs to $5.04/ million BTUs (**Fig. 2**). Each additional highway mile will increase the energy cost by $0.04/ million BTUs. Similar procedures showed that each additional mile of unpaved road and spur road would result in an increase in the energy cost by $0.13/million BTUs and $1.48/million BTUs, respectively.

Diesel price directly affected system production cost and energy cost. Market diesel prices in effect during the study period were $2.90/gal for off-highway diesel and $3.20/gal for on-highway diesel, resulting in the energy cost of $4.65/ million BTUs. Average diesel price was set at $1, $2, $3, and $4 per gallon in the sensitivity analysis and the price difference between on-highway and off-highway diesel was omitted. With an increase of diesel price by one dollar per gallon, the overall energy cost increased by $0.34/million BTUs (**Fig. 3**).

Discussion

Higher energy costs resulted on unpaved roads and spur roads compared to highways because the energy output did not change and the regression coefficients reflected that unpaved and spur roads distances had stronger effects on travel time than highway mileage. Reducing off-highway hauling should receive more attention than reduction in on-highway mileage in harvest planning work. The hauling energy input represented 36.27 percent of the total energy input, while the percentage for transporting machines was 14.77 percent. These high energy consumption percentages emphasize the importance of operations close to markets and the value of nearby available machines.

The net energy ratios from 18.2 to 25.0 were found by Adams (1983) for harvesting stems 4 to 8 inches in diameter and 4 to 10 feet in length using a cable system. Energy used for hog fuel hauling was not included. In our study, the net energy ratio would have been 16.33 if hauling energy input was excluded. A lower production rate for harvesting smaller trees was the major influence on the net energy ratio because it required more time and energy to harvest the same weight of biomass.

Use of forest biomass for energy compares well with other biomass sources in net energy ratio. Our forest biomass energy study found the net energy ratio to be 10.41 when utilizing ponderosa pine biomass. Keoleian and Volk (2005) reported the net energy ratio of 9.9 for willow biomass crops that are direct-fired, while Shapouri et al. (1995) found a net energy ratio of 1.24 when converting corn to ethanol. Other studies reported −33,517 BTUs/gal and −8,431 BTUs/gal (energy loss) when producing corn-based ethanol (Pimentel 1991, Keeney and Deluca 1992). However, the net energy ratios reported here were on the high end of this range as energy input for possible active drying, storage, and final delivery was not included. These energy inputs depend on the technology used and are often difficult to estimate.

The major factor that can impede the use of forest biomass for energy is the high production cost and energy cost associated with harvesting forest biomass for energy. The production cost of $53.15/BDT found by an accompanying cost study (Pan et al., 2007) illustrated that it was difficult to break even given the current hog fuel price in the market. The energy cost of $4.65/million BTUs did not include the costs for energy conversion and final delivery, which would lead to a high energy cost in the end.

Conclusions

Energy input and output were monitored in a 9-day operation for harvesting and processing ponderosa pine trees less than or equal to 5.0 inches in DBH and for transporting processed hog fuel for energy. The total fossil fuel energy input equaled 369,006,100 BTUs. Direct and indirect energy input represented 75.65 percent and 24.35 percent of the total energy input, respectively. Lab experiments found the average recoverable heating value of 2,699.4 BTUs/pound for the processed hog fuel at the MC of 52.75 percent. The hog fuel from unit 3 was the driest of the four units and had the highest recoverable heating value despite of the smallest size of the trees. Biomass fuel that is directly fired can be significantly affected by natural events such as rainfall. The total recoverable energy output was 3,840,382,392 BTUs for 336.11 bone dry tons (711.34 green tons, MC at 52.75%) of hog fuel. The net energy output was 3,471,376,292 BTUs with a net energy ratio of 10.41. The lower net energy ratio of this study compared with findings from other forest biomass energy studies was a function of harvesting and processing smaller trees. This had the effect of lowering the production rate of the system. Harvesting larger size material should improve the net energy ratio.

Energy used for hauling hog fuel represented the largest part (36.27%) of the total input energy. Each mile of hauling distance increase would decrease the net energy ratio by 0.11. Energy cost would increase $0.04/million BTUs, $0.13/million BTUs, and $1.48/million BTUs for each additional mile of highway, unpaved road, and spur road, respectively. This indicates the importance of operations close to markets and of planning that can reduce off-highway hauling. Energy consumed for moving machines accounted for 14.77 percent of the total energy input, emphasizing the value of nearby available machines. A diesel price change of $1/gallon positively affected the energy cost by $0.34/million BTUs.

Using forest biomass for energy is encouraging compared with using other biomass sources in terms of net energy ratio. The high production cost and energy cost associated with mechanical harvesting of forest biomass, however, are the major factors that can impede the use of forest biomass for energy. Further research in lowering forest biomass production cost and energy cost is needed.

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