Assessment of the Pre-Plant Environmental Impacts of a Biomass Fuels System at Rock-Tenn

The Green Institute
Dr. Steven J. Taff
Carl Nelson

Produced under contract for
Saint Paul Port Authority

July 2008

THE GREEN
INSTITUTE

Introduction

This report was produced as part of an effort to assess potential environmental impacts and benefits of replacing the Rock-Tenn Company's St. Paul Recycled Paper Mill's current natural gas and fuel oil boilers with a biomass fuel system. The Green Institute's scope of work considers "upstream" life cycle impacts up to the potential power plant's gate. That is, the impacts of producing, collecting, and transporting biomass are considered, but impacts at the power plant, such as air emissions from combustion, as well as other "downstream" impacts at the plant and beyond are not considered here. We refer to these impacts as "pre-plant" impacts.

Specifically, the objectives of this analysis are:

- Estimate the pre-plant life-cycle air and water emissions of key pollutants from the production, collection, processing and transport of corn stover, grasses and forest wood biomass from a hypothetical biomass fuel system, as compared to a reference case; and
- Provide a preliminary estimate of the net energy and carbon balance of a hypothetical biomass fuel system.

This type of analysis necessarily relies upon assumptions and professional judgments, which we have attempted to make transparent to the best of our ability. Given the uncertainties inherent in the calculations and assumptions used for the analysis, the central estimate results presented here should be interpreted as a best estimate given the data available to us. We would estimate the uncertainty of the central estimates to be generally accurate within about a factor of two; i.e., from 50% to 150% of the central estimate. Actual impacts could be much greater or less should a major assumption of the hypothetical biomass fuel system prove not to be correct. For example, our assumption that forests would be allowed to re-grow after biomass is harvested (and therefore would re-capture carbon), if incorrect, would dramatically impact the accuracy of our carbon balance calculation.

Methodology

We use a life-cycle analysis to calculate the impacts of all production processes that directly impact the feedstock up to the plant gate, plus the processes that provided the fuel and chemicals used in the growing, management, harvesting, and transporting of the biomass. In addition, we consider the immediate further upstream impacts due to the manufacturing of the equipment used in these processes – for example emissions from the manufacturing of harvest equipment.[1]

---

[1] Numerous studies have shown that impacts from the manufacture of equipment is a very small portion (on the order of one to two percent) of the total energy and emissions impacts of any of the biomass sources we consider here.

Impacts calculated

We estimate the pre-plant emissions for the following:

- Fossil-fuel energy inputs (Btu)
- Greenhouse gases:
    - carbon dioxide (CO_2)
    - methane (CH_4)
    - nitrous oxide (N_2O)
- Other air pollutants:
    - volatile organic compounds (VOC)
    - carbon monoxide (CO)
    - nitrogen oxides (NO_x)
    - particulate matter less than 10 microns (PM_{10})
    - particulate matter less than 2.5 microns ($PM_{2.5}$)
    - sulfur oxides (SO_x)
- Water pollutants:
    - nitrate nitrogen (NO_3)
    - phosphorous (P)

Model and conceptual framework for calculations

To estimate energy inputs and air emissions (including greenhouse gases), we used GREET, a life-cycle analysis model for biofuels developed by Argonne National Laboratory.[2] GREET is widely used primarily to assess environmental impacts of liquid biofuels.[3]

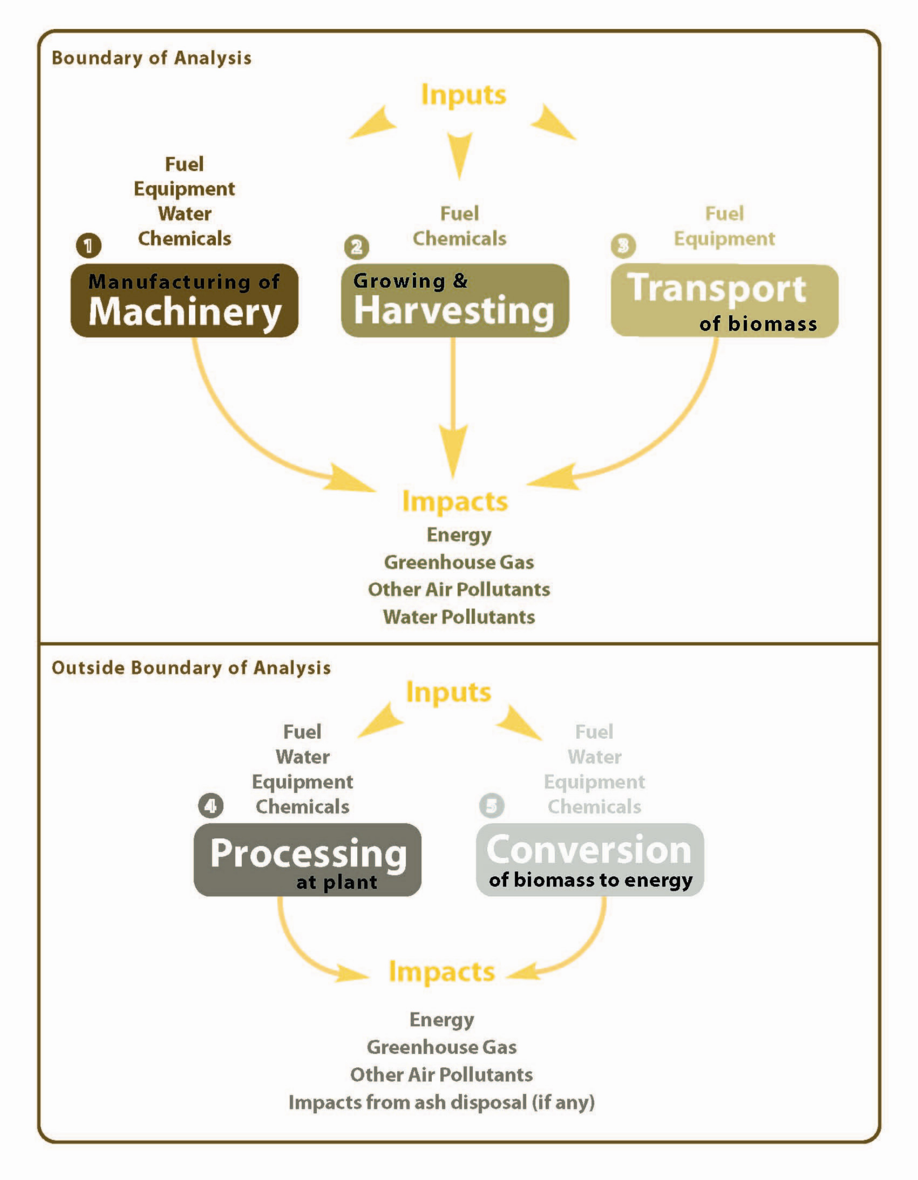
Figure 1 outlines the entire feedstock fuel process, demonstrating the impacts that are estimated by the model. We examine three major biomass fuel feedstocks: corn stover, grasses (representative of perennial prairie grass), and forest wood. We also estimate energy and environmental impacts for two fossil-fuel scenarios, a fuel oil/natural gas blend (75% fuel oil/25% natural gas) and a 100% natural gas scenario. We do not estimate impacts at the plant.

---

[2] GREET stands for "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation." See http://www.transportation.anl.gov/software/GREET/. The model is described in the user manual: M. Wang, Y. Wu, and A. Elgowainy. Operating manual for GREET: Version 1.7. Argonne National Laboratory. ANL/ESD/05-3. rev. Feb. 2007. We used version 1.8a, dated August 2007.

[3] For example, GREET was used for the following recent widely-reported study on land use impacts of ethanol production: Searchinger, et al. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change." Science. Vol 319, pg. 1238. February 29, 2008.

Figure 1: Boundary and impacts of The Green Institute life cycle assessment analysis



Assumptions of the GREET model

We adjusted crop production systems assumptions to suit Minnesota conditions and to track energy and emissions data through several stages: biomass production, collection, processing and delivery to the plant. Except where otherwise noted, we use the default parameter specifications in GREET. We report some of the many parameters used in GREET, and all of those that were changed from the default, in the appendix (see Table A-1). In many cases, these parameters are recognized to have wide variability.

The actual energy and pollution outcomes will vary according to exactly where the crops are grown, how they are managed and harvested, how far they are transported, if biomass usage causes land-use changes, and a variety of other factors, many of which are identified in the appendix. We necessarily use average, representative systems in this analysis, but we believe these averages are representative of actual system conditions should Rock-Tenn choose to employ one or more of these feedstocks. We do not calculate the economic value of the energy and environment impacts. We assume that all products are transported by truck to Rock-Tenn for an average distance of 100 miles.

Should a biomass fuel system result in land use changes, additional environmental impacts may result that are not calculated here. We assume that all corn stover, grass, or wood comes from land already growing corn, grass, and trees, respectively. Thus no land use change occurs as a result of Rock-Tenn feedstock procurement; either directly, in that land currently in an annual crop is changed to grass for example, or indirectly, in that Rock-Tenn's procurement program increases the price of the feedstock so that other lands (in Minnesota or elsewhere in the world) are changed in response. This is a reasonable assumption because there are already sufficient quantities of stover and wood in the region, so no new land would need to be converted to meet the full demand of Rock-Tenn with these sources. For grasses, it is highly unlikely that existing annual crop lands would be converted to grow grass at expected commodity price levels - annual crops simply provide too much profit for farmers to find it financially prudent to switch to grass at any price likely to be paid by Rock-Tenn. However, should additional public subsidies be available for grasses, they could result in land use change. The positive or negative impacts of this potential land use change are not calculated in this analysis.

A corollary to our assumption of no land use change is that we also assume that current corn, grass, and forest systems are "stable" in the sense that under sustainable management these systems neither add to nor subtract from the soil's carbon or nutrient profiles. In this assumption, landowners exactly match nutrients removed through harvest with nutrient supplements. Lands converted to grass may initially sequester carbon; however, the GREET model assumes that stable grass systems do not sequester significant quantities of carbon on an annual basis.

For forest harvests, we start with the GREET default values for energy and emissions. Wu et al. estimate that forest harvests require significantly more diesel fuel than do agricultural harvests.[4] This difference is especially evident in the base case energy use assumption that forest wood requires more than twice as much fossil energy per ton removed as does corn stover harvest (613,000 Btu per dry ton and 235,000 Btu per dry ton, respectively). In the sensitivity section we examine the implications of lesser energy use for forest wood removal.

Finally, we assume that the only greenhouse gas released during decomposition (if the biomass feedstocks were allowed to decompose in the field) is CO_2. In reality, under certain management and climate conditions, decomposition could result in N_2O and/or CH_4 emissions, resulting in higher greenhouse gas emissions than just CO_2 alone. As a result, the combustion

---

[4] Wu, M., M. Wang, and H. Huo. Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States. Argonne National Laboratory. ANL/ESD/06-7. November 2006.

of biomass could result in a reduction of these types of N_2O and CH_4 emissions since the feedstocks would be combusted instead of decomposing. However, these processes are not well characterized, and we make the conservative assumption that N_2O and CH_4 emissions from decomposition are negligible.

One shortcoming of using GREET to analyze non-liquid biofuels is that it does not consider the fuel processing impacts that in practice may occur prior to reaching the plant, like chipping wood at a forest landing rather than inside the plant, as is likely for any Rock-Tenn forest wood procurement.[5] Although processing is likely to occur pre-plant for wood, this is not likely to be the case for grasses and corn stover. It is expected that grasses or corn stover would be delivered in bales to a Rock-Tenn plant, and processed inside the plant boundaries, as is modeled in GREET.[6] Thus for forest wood the pre-plant impacts presented here are under-estimated, in that they don't include processing impacts, while for grasses and corn stover, the GREET assumption of no fuel processing prior to delivery to the plant is valid. Using an estimate from the literature, inclusion of the life-cycle fossil fuel cost of wood chipping could increase fossil energy use by 3,657 Btu/MMBtu and CO_2 emissions by 0.57 pounds CO_2/MMBtu from the results presented below (about a 4% increase).[7] However, because this is a process not calculated pre-plant in GREET, and for consistency across fuel types, we do not include fuel processing in our reported totals.

Water impacts

GREET does not calculate water impacts; thus we estimate surface water impacts separately from GREET. Water impacts result from the addition of fertilizer combined with erosion or subsurface drainage that deliver nutrients to the water system. Nutrient flows to the water system vary each year on every acre of cropland.

For corn stover, we use regional averages. We assume a "typical" Minnesota well-drained medium organic soil, eroding at 5 tons per acre per year for corn and 0 tons per acre per year for grass and trees on the same soil.[8] We assume that all nutrients leaving the field eventually end up in the water somewhere: none is deposited permanently on downhill fields. For erosion rates at this level we expect approximately 15 pounds of nitrate nitrogen to leave a corn field with the sediment, plus 5 pounds of phosphorus. In addition, we assume that 5 pounds of nitrate nitrogen will leach into tile lines or groundwater. (Nitrate losses from fields can vary by 100% from these figures, depending upon soil, landscape position, weather, and crop

---

[5] Wu, Mae. Argonne National Laboratory. Personal communication. July 2, 2008.

[6] It is worth noting that hammermills or other fuel processing equipment used at the plant site would likely be run with electric motors, as opposed to diesel engines, which are the norm for processing forest wood off-site. In general, electric motors would have a lower emissions profile from many air pollutants compared to diesel engines.

[7] This is for a 500HP hammer mill operating at 50T/hour. Katers, J. F. and J. Karuich, University Wisconsin Green Bay, Net Energy Study as commissioned by Pellet Fuels Institute, presentation to PFI Annual Conference, n.d.

[8] "Economic and environmental implications of alternative landscape designs in the Walnut Creek Watershed of Iowa," Ecological Economics, Volume 38, Issue 1, July 2001, Pages 119-139, Colette Coiner, JunJie Wu and Stephen Polasky.

management.) Change in this flow would occur only if land use changes, and we assume that it does not in the present analysis.

All these nutrient movements will occur whether or not stover is removed; they are largely due to the annual exposure of bare soil to spring rains. Thus the impacts assigned to a biomass crop like corn stover will vary based on what proportion of the pollution is assigned to the grain versus the stover. Corn stover is traditionally treated as a residue, and none of the costs, economic or environmental, of growing corn are typically assigned to the residue portion. We argue that this allocation is inappropriate. Corn stover is a product of corn production that farmers will be paid to produce, just as is corn grain. Consequently, some of the costs (economic, energy, and emissions) of growing corn should be assigned to corn stover. Our base case is a 15% allocation that results from using the relative gross returns from each product: 2 tons of stover at $60/ton and 160 bushels of corn at $5.00/bushel.

Assuming the default 15% allocation, each ton of stover (at a 2 tons/acre/year removal rate) is responsible for (15+5)*.15=3 pounds of nitrate nitrogen and 5*.15=.75 pounds of phosphorus entering water. If the nutrient pollution is assumed to be 100% allocated to the corn grain, as is conventional, then the stover itself would not be assigned any incremental water pollution. The estimated water pollution effects of corn stover, grasses, and forest wood are shown in Table 1.

For grass or forest systems, we assume that any biomass removal would meet Minnesota sustainable harvest guidelines.[9] Additionally, we assume that the perennial nature of these systems will lead to no erosion and, hence, no loss of nutrients from the site.

Table 1: Water pollution effects of biomass crop removal (pounds per ton)

Crop	Nitrate-Nitrogen	Phosphorus
Corn stover	3.0	.75
Grasses	-	-
Forest wood	-	-

Results

Figures 2 through 6 summarize the principal results of this study. The source data for the charts is also presented in the appendix, Tables A2-A6. Figure 2 shows the life-cycle energy use for each pre-plant production stage for each biomass feedstock. The units are on a per-dry-ton basis. Actual feedstock procurement will likely be based on wet tons, or actual weight, but we convert to dry tons to permit comparison across feedstocks.[10]

---

[9] Minnesota has guidelines for timber and forest residue removal, but not (yet) for grass or corn stover harvesting.

[10] Typical moisture content is 15-20% moisture for corn stover and grass and 40-50% for forest wood.

CO_2 emissions are depicted in Figure 3. Because methane (CH_4,) and nitrous oxide (N_2O) are greenhouse gases with far stronger climate effects than CO_2 on a per ton basis, we calculate what is called the "CO_2 equivalent," here referred to as CO_2e, which weights the three major greenhouse gases by their actual effect on the atmosphere. We use the standard Intergovernmental Panel on Climate Change (IPCC) global warming potential factors: 296 for N_2O, 23 for CH_4, and 1 for CO_2. The relative contributions to the emissions profiles are shown in Figure 4. In that figure (and in Figure 5), we include the estimates for natural gas alone and for a 75/25 residual fuel oil/natural gas feedstock portfolio.

Figure 5 shows the other air pollutants calculated by GREET for each feedstock. The principal source of NO_x for corn stover and grass is the nitrogen fertilizer supplement required if biomass is removed from the field, while the main source of SO_x is from what GREET refers to as "chemicals" (fertilizers and pesticides), mostly from burning coal to produce the electricity required to make fertilizer.

Figure 6 details the forest wood system with respect to the other air pollutants, again on a pre-plant basis. The principal source is field work, mostly from the high fuel consumption associated with harvest. In the sensitivity section below, we examine the effect of reducing the assumed level.

Although there is some difference among biomass feedstocks for all the pollutants, in the aggregate the variations among biomass feedstocks are on the order of the total uncertainty of our estimates. Grasses have a slightly larger impact from "chemicals" principally because of the supplemental nitrogen required to make up for nutrient removals. Corn stover does not have this requirement because it is assumed to be grown in a corn-soybean rotation, and carry-over nitrogen from the previous soybean year is assumed to be sufficient to make up for removals. In addition, only forest wood systems are assumed to require no chemical supplements.

Figure 2: Total life-cycle fossil energy use for biomass feedstocks at each pre-plant production stage

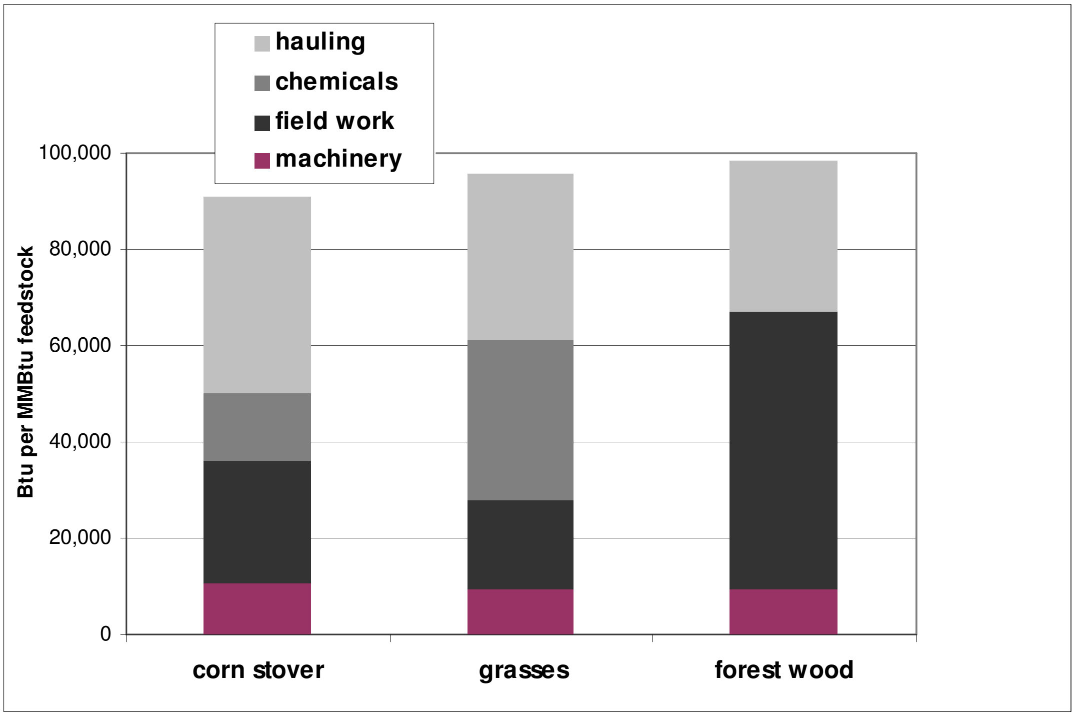


Figure 3: Total life-cycle CO_2 emissions from biomass feedstocks at each pre-plant production stage

Figure 4: Total life-cycle CO_2e emissions for feedstocks from pre-plant production

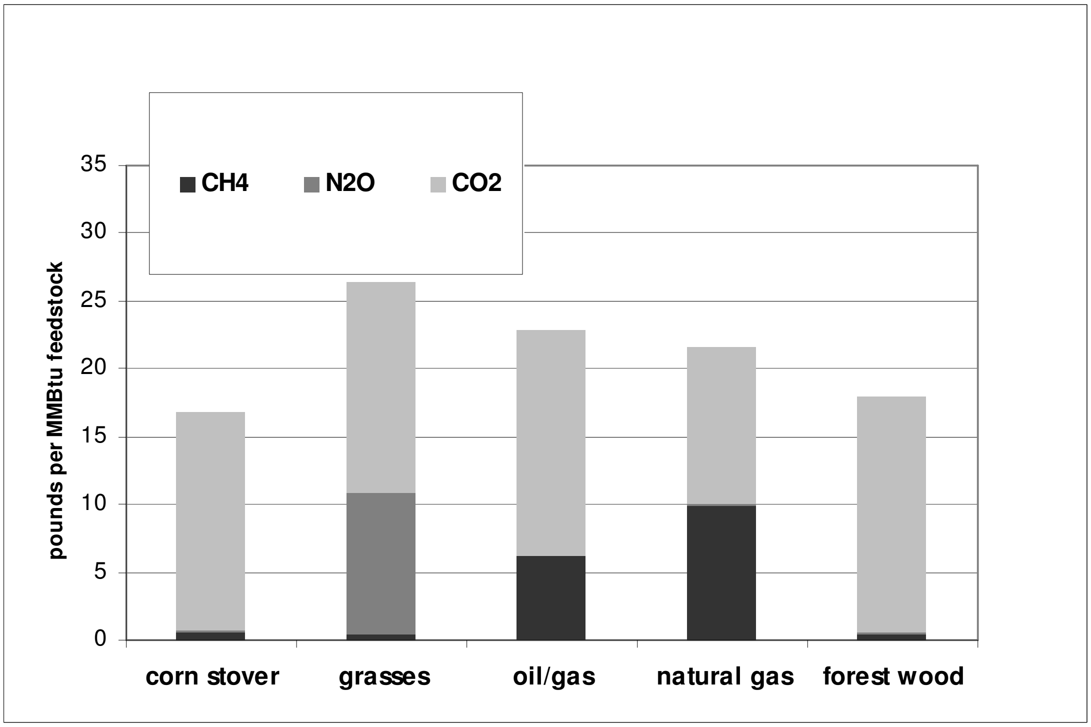


Figure 5: Total life-cycle non-GHG emissions for feedstocks from pre-plant production

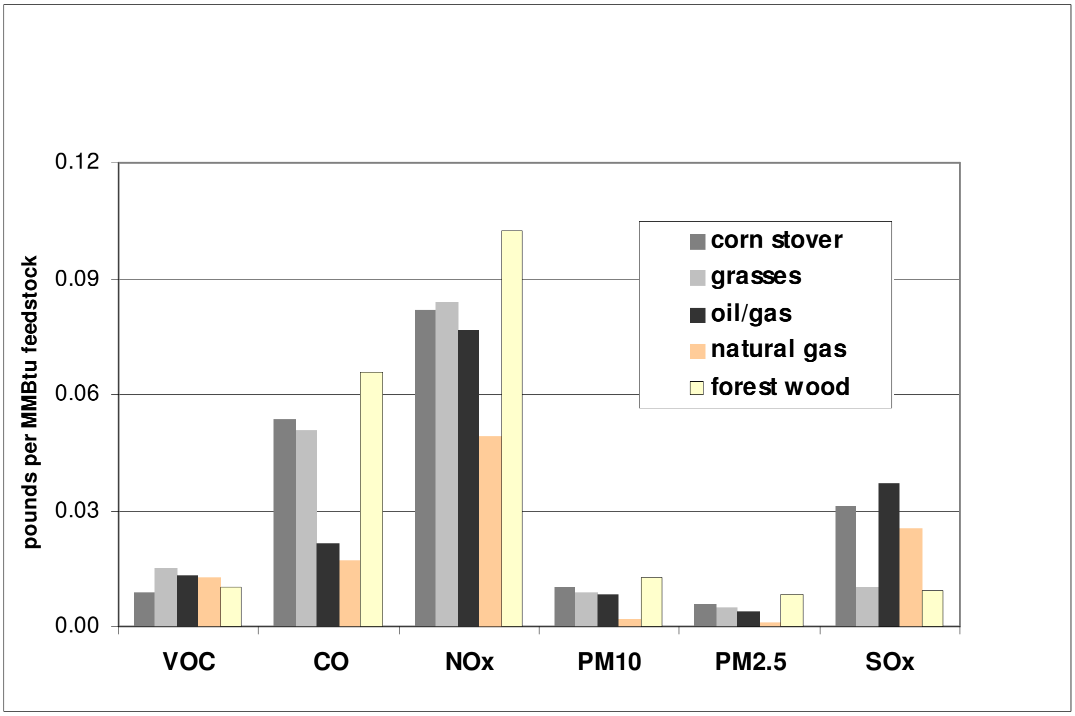
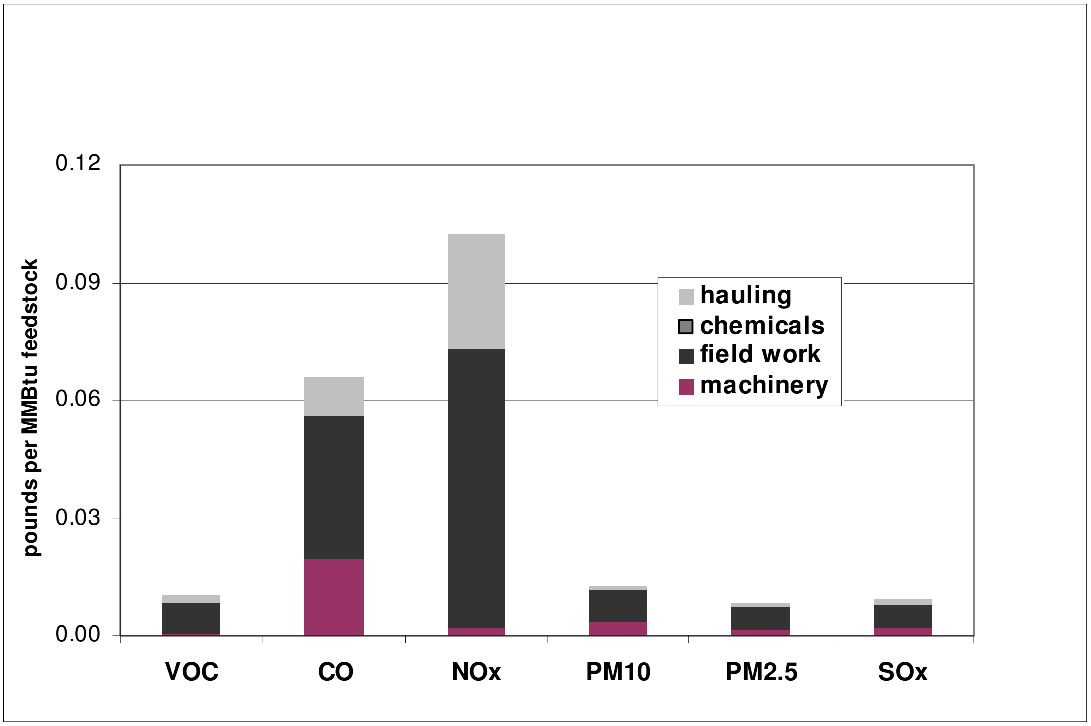


Figure 6: Total life-cycle non-GHG emissions for forest wood for each pre-plant production stage



Sensitivity analysis and uncertainty

Feedstocks such as corn stover are commonly termed "residues" but are more accurately termed "co-products" as farmers will be able to receive income from the corn stover as they receive income from the grain. A determinant of the environmental impact of corn stover is how much of the biomass planting and tending processes we assign to the main crop (corn grain) and how much to the co-product (stover). It has been customary in the greenhouse gas (GHG) literature to assign all seedbed preparation, planting, nutrient and pesticide applications, cultivation and grain harvest expenses (and their associated GHG emissions) to corn grain and only the stover baling expenses (and associated emissions) to the stover. This obviously has the effect of making the grain look worse and the stover better than would be the case if the costs of preparation etc. were assigned more equally to the two products, corn grain and corn stover. In Table 2, we show how life-cycle energy and emission estimates would change if we were to assign half the impacts of growing corn to the stover. The 50% allocation is based on mass of product removed; at the assumed production rate for grain, approximately 4 tons each of grain and stover are produced on the land. Under this scenario, corn stover fossil energy use and CO_2 emissions are slightly higher than for both forest and grasses biomass.

Table 2: Effect of treating corn stover as a co-product of corn production on pre-plant environmental impacts

Percent of corn growing impacts allocated to stover	Fossil energy (Btu/MMBtu)	CO_2e (lbs/MMBtu)	NO_x (lbs/MMBtu)
0	76,790	13.98	.07
15	91,161	16.77	.08
50	104,967	19.45	.09

Much of the biomass energy analysis conducted prior to the recent dramatic increases in land and crop prices showed the importance of distance in the economic calculus: the farther the feedstock source from the plant, the more expensive the feedstock at the plant gate. The same holds for the energy and emission life-cycle impacts, as Table 3 shows for the case of forest wood. (Stover and grass would show similar results.) The farther the feedstock is shipped, the more transport fuel is consumed, the higher the resulting emissions from combustion of that fuel. A frequent point made in discussions of biomass procurement is that hauling costs are paramount: the farther away from the plant, the more expensive (in economic, energy, and emissions terms) is the feedstock. In Table 3, we see that distance matters, but not as much as might be expected. For example, if the hauling distance for corn stover is tripled (from 50 miles to 150 miles), the greenhouse gas emissions (up to the plant gate) are not tripled; they increase by about 56 percent.

Table 3: Effect of required hauling distance on pre-plant environmental impacts

	Corn stover			Forest Wood		
Miles to plant	Fossil energy (Btu/MMBtu)	CO_2e (lbs/MMBtu)	NO_x (lbs/MMBtu)	Fossil energy (Btu/MMBtu)	CO_2e (lbs/MMBtu)	NO_x (lbs/MMBtu)
50	70,672	13.11	.06	82,772	15.15	.09
100	91,161	16.77	.08	98,542	17.96	.10
150	111,649	20.42	.10	114,312	20.78	.12

One of the reasons for the relatively high energy and pollutant profiles for forest wood is the high energy consumption assumed in GREET—and accepted by the authors for the base analysis—for management and harvest stages. Table 4 shows how some of these results would change were we to assume instead dramatically lower or higher energy use for this production activity, as might be the case if Minnesota forest harvest energy profiles—if ever measured—proved to be less diesel-intensive than the base case. For example, if the wood could be harvested and brought to the landing at a life-cycle cost of 1.38 gallons of diesel, as opposed to the GREET base case of 2.38 gallons per ton, the direct fossil energy use (the largest portion of the life-cycle costs) would decrease by over 200,000 Btu per dry ton of harvested wood.

Table 4: Effect of alternate energy use assumption for forest wood production on pre-plant environmental impacts

Energy use in production (Btu/dry ton)	Fossil energy (Btu/MMBtu)	CO_2e (lbs/MMBtu)	NO_x (lbs/MMBtu)
400,000	78,586	14.35	.08
612,700	98,542	17.96	.10

Calculating the carbon advantage of biomass

Biomass sources are often referred to as "carbon neutral," based on the argument that the CO_2 released by combusting biomass for energy is equal to the CO_2 the plants absorb from the atmosphere as they grow. In practice, no biomass fuels are truly carbon neutral because some greenhouse gases are emitted in the production, collection, processing and transport of biomass, as we have shown in this analysis. In addition, other consequences of establishing a biomass fuel system, such as land use changes caused by biomass use, can result in additional CO_2 emissions. Further, the benefits of using biomass depend upon what energy source is being replaced. Thus a more useful framework than "carbon neutrality" is to consider the "carbon advantage" of biomass over other alternatives. This is one reason we include a reference case in our results.

The relative carbon advantage of a biomass fuel system is dependent upon assumptions about the appropriate temporal scope of the analysis. For corn or grass systems, biomass uptake and removal recurs annually; for trees, it could be ten years (for short-rotation trees like hybrid poplars) or even fifty years or more (for forest trees); for fossil fuels, it is millions of years. For any of these fuel systems to be considered "carbon neutral" with respect to balancing the carbon uptake of the system with the carbon release, two conditions must be met:

(1) The periodic removal rate cannot exceed the cumulative re-stocking between periods; and
(2) The stated length of time is the proper scope for carbon accounting.

There is no commonly accepted temporal standard for carbon accounting. In practice, most analysts draw the line at 100 years or less, which we assume here. We assume the biomass systems considered here meet the above two conditions, while fossil systems (with a timeframe for carbon uptake of millions of years) do not.

Another method would be to "discount" the carbon neutrality of biomass systems over the time it requires to fully uptake the carbon released when the biomass is combusted. While appealing in concept, in the absence of existing research and clear methodology for applying this theory, we do not employ a discounting approach here.

Another factor to consider is emissions from combustion from nitrous oxide and methane, also greenhouse gasses. These are emitted in small quantities, but have high global warming potential. We calculated potential N_2O and CH_4 emissions based on generic emission factors from the Intergovernmental Panel on Climate Change, and converted these factors to CO_2

equivalents, as for the life-cycle costs above.[11] As these estimates are based on generic emission factors, the estimates should be considered preliminary; it may be possible to develop better estimates when more specific information on the conversion technology is available.

Table 5 presents the net carbon release of biomass fuels compared to fossil sources, on an MMBtu basis. Note that this is over a temporal scope of less than 100 years, over which the carbon uptake from fossil sources are negligible. The net effect does not include fuel processing and other energy requirements at the plant that may release additional carbon.

Table 5: Net carbon emissions of biomass fuels compared to fossil sources (exclusive of fuel processing and other life-cycle energy requirements at the plant)

	Pounds CO_2e per MMBtu feedstock[12]				
	Forest wood	**Grasses**	**Corn stover**	**Natural gas**	**Fuel Oil**
Carbon uptake	195	227	219	--	--
Production/delivery	18	28	17	21	23
At plant & fuel processing	n/a	n/a	n/a	n/a	n/a
CO_2 emissions from combustion	195	227	219	117	161
N_2O and CH_4 emissions from combustion	21	21	21	1	0
Net CO_2e release	**39**	**49**	**38**	**139**	**184**

This should be considered a preliminary and incomplete calculation, as it does not include the life-cycle CO_2 emissions for fuel processing or other activities at the plant from (for example) fuel conveying, energy requirements at the plant, steel and concrete used to build the plant, etc. This calculation could be further refined with emission rates for N_2O and CH_4 more specific to a Rock-Tenn facility than the generic factors used here.

Net energy balance of a biomass fuel system

The net energy balance is typically expressed as a ratio of energy output to energy input. Since our analysis ends at the plant, we calculate the net energy balance for the embedded energy in the biomass when it is delivered to the plant. The results presented in Table 6 demonstrate that 10-11 times more energy is available when the fuel reaches the plant gate for the three biomass sources considered here than is consumed in producing, collecting and transporting the

---

[11] Intergovernmental Panel on Climate Change (IPCC), "2006 IPCC Guidelines for National Greenhouse Gas Inventories," prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. IPCC reports in kg/TJ, we convert to lbs/MMBtu and use carbon equivalents of 23x for CH_4 and 296x for N_2O. Specific emission factors for grasses and corn stover were not available, so we used the category "other primary biomass fuels" for the emissions estimates from these fuel sources.

[12] CO_2 content of fuels for wood, fuel oil and natural gas from Energy Information Administration (www.eia.doe.gov/oiaf/1605/coefficients.html); corn stover and grasses were derived from AURI fuel content testing conducted by Minnesota Valley Testing Laboratories, July 2007 based on molecular ratio of CO_2 to C. Combustion assumes 100% oxidation level.

biomass. Forest wood has a slightly lower net energy balance due to the higher energy requirements of collection. These ratios don't include the energy cost of any inside-the-plant conversion of the feedstock into a useful energy source or processing the fuel, which is outside the scope of this study. For forest wood, including the energy requirements of grinding the wood in the forest would further reduce the net energy balance to 9.6.[13]

Table 6: Net energy balance of biomass sources at the plant gate (exclusive of fuel processing and other energy requirements at the plant)

Biomass source	Net Energy Balance
Corn stover	10.8
Grasses	10.3
Forest wood	10.0

Conclusions

1. The surface water pollution impacts of corn stover are highly site-specific and dependant upon how much of the pollution is assigned to the corn stover versus the corn grain. Here we depart from convention and assume corn stover will be assigned some of the water pollution impacts (Table 1). The surface water pollution impacts from grasses and forest wood are expected to be negligible, as long as sustainable removal guidelines are followed.

2. We estimate that total pre-plant energy requirements of collecting, harvesting and transporting biomass to Rock-Tenn vary from about 90,000 to 100,000 Btu/MMBtu of feedstock delivered (Figure 2). This translates to a net energy balance of 10 to 11 times more useful energy produced than energy expended in collection, harvesting and transport (Table 6). This is an incomplete estimate of net energy balance, as it does not include the inside-the-plant energy requirements to convert the biomass to useful energy.

3. We estimate emissions of greenhouse gases from collecting, harvesting and transporting biomass to Rock-Tenn to vary from 15 to 30 pounds of carbon dioxide equivalent per MMBtu of energy contained in the fuel (Figure 4). This is roughly on par with the pre-plant greenhouse gas emissions of natural gas and fuel oil. These impacts are overshadowed by the potential carbon advantages of biofuels (Table 5), which show the net greenhouse gas emissions of fuel oil and natural gas to be approximately 3-5 times greater than the biomass sources considered here.

4. Pre-plant emissions of particulate matter are significantly lower for natural gas than for biomass or fuel oil (Figure 5). It is harder to make generalizations about other pre-plant non-greenhouse gas emissions, which in some cases are higher for natural gas and fuel oil than are some biomass sources, and in other cases somewhat lower.

---

[13] Using the same study referenced in footnote # 7. Use of different methods for chipping or grinding could have further implications for the net energy balance.

APPENDIX

Table A-1: Key parameters in GREET, as adapted for Rock-Tenn study. Gray-shaded areas were changed from GREET base-case defaults.

Ag Inputs							
	Ammonia (NH_3)	Urea (NH_2CONH_2)	Ammonium Nitrate (NH_4NO_3)		Phosphate (P_2O_5)	Potash (K_2O)	$CaCO_3$
Ratio of Nutrient to Product for Fertilizer	0.824	0.467	0.35		1	1	1
	Atrazine	Metolachlor	Acetochlor	Cyanazine			
Shares of Herbicide Types for Crop Type							
Corn	0.312	0.281	0.236	0.171			
Farmed Trees	0.25	0.25	0.25	0.25			
Herbaceous Biomass	0.25	0.25	0.25	0.25			
Corn Stover	0.25	0.25	0.25	0.25			
Wood Residue	0.25	0.25	0.25	0.25			
Sugar Cane	0.25	0.25	0.25	0.25			
Soybeans	0.362	0.638	0	0			
Inputs							
N content of above and below ground biomass							
	Corn Farming	Biomass Farming	Corn Stover				
	141.6	0	0				
N_2O emissions: N in N_2O as % of N in N fertilizer and biomass							
	Corn Farming	Biomass Farming	Corn Stover				
	0.013	0.013	0.013				
N_2O credit from corn stover removal							
	N Content of Corn Stover	N in N_2O Avoided per Unit of N in Stover Removed					
	0.0045	0					
Farming Energy Use and Fertilizer use							
		Corn (Btu per bushel)	Farmed Trees (Btu per dry ton)	H. Biomass (Btu per dry ton)	Corn Stover (Btu per dry ton)	Forest Residue (Btu per dry ton)	
	Farming Energy Use: Btu	22,500	234,770	217,230	235,244	612,700	
	Fertilizer						

	Use					
	Grams of Nitrogen	368.875	709	10,635	-	0
	Grams of P2O5	141.875	189	142	1,633	0
	Grams of K2O	198.625	331	226	8,346	0
	Grams of CaCO3	851.25	0	0	0	0
	Pesticide Use					
	Grams of Herbicide	14.1875	24	28	0	0
	Grams of Insecticide	0.141875	2	0	0	0
Moisture Content of Biomass When Being Transported						
	Farmed Trees	0.42				
	Herbaceous Biomass	0.15				
	Corn Stover	0.25				
	Forest Residue	0.42				
	corn grain	0.15				
Transportation and Distance Flow Charts						
corn grain hauling miles (one-way)	100					
corn stover hauling miles (one-way)	100					
farmed tree hauling miles (one-way)	100					
herbaceous biomass hauling miles (one-way)	100					
forest residue hauling miles (one-way)	100					
Transportation and Distance						
corn grain heavy duty truck payload (tons)	20					
corn stover heavy duty truck payload (tons)	14					
farmed trees heavy duty truck payload (tons)	25					
herbaceous biomass	14					

heavy duty truck payload (tons)	
forest residue heavy duty truck payload (tons)	25
ETOH	
Calculations of Energy Consumption and Emissions for Each Stage	
Fuel Specs	
Solid Fuels:	Btu/ton
Farmed trees	16,811,000
Herbaceous biomass	14,797,555
Corn stover	14,075,990
Forest residue	13,243,490
corn grain	17,000,000

Table A-2: Estimated pre-plant life-cycle energy (Btu/MMBtu output) and emission impacts (lbs/MMBtu) for Corn Stover

	machinery	field work	Nitrogen	P2O5	K2O	CaCO3	Herbicide	Insecticide	chemicals	hauling	**TOTAL**
Total energy	164	36,380	4,656	2,060	5,453	1,806	1,031	12	15,019	41,087	92,651
Fossil fuel total	10,604	25,288	4,598	1,973	5,059	1,664	987	12	14,294	40,974	91,161
Coal	10,067	(4,990)	287	431	1,947	700	218	3	3,585	1,120	9,782
Natural gas	3,799	4,806	4,125	946	1,524	544	275	3	7,416	2,151	18,172
Petroleum	5,410	16,801	187	597	1,589	420	495	6	3,293	37,703	63,207
non-fossil fuel	(10,440)	11,092	58	87	394	142	44	1	726	113	1,491
VOC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
CO	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05
NOx	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.08
PM10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
PM2.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
SOx	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.03
CH4	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
N2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	2.09	4.52	0.62	0.34	0.95	0.31	0.18	0.00	2.39	7.07	16.08

Table A-3: Estimated pre-plant life-cycle energy (Btu/MMBtu output) and emission impacts (lbs/MMBtu) for Grasses

	machinery	field work	Nitrogen	P2O5	K2O	CaCO3	Herbicide	Insecticide	chemicals	hauling	TOTAL
Total energy	9,938	18,884	32,993	128	129	-	499	-	33,748	34,486	97,055
Fossil fuel total	9,521	18,487	32,580	122	119	-	478	-	33,299	34,391	95,698
Coal	3,533	2,162	2,030	27	46	-	106	-	2,208	940	8,844
Natural gas	5,133	1,428	29,225	59	36	-	133	-	29,452	1,806	37,818
Petroleum	855	14,897	1,325	37	37	-	239	-	1,639	31,645	49,036
non-fossil fuel	417	397	413	5	9	-	21	-	448	95	1,357
VOC	0.00	0.00	0.01	0.00	0.00	-	0.00	-	0.01	0.00	0.01
CO	0.02	0.01	0.01	0.00	0.00	-	0.00	-	0.01	0.01	0.05
NOx	0.00	0.02	0.01	0.00	0.00	-	0.00	-	0.01	0.03	0.08
PM10	0.00	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00	0.01
PM2.5	0.00	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00	0.00
SOx	0.00	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00	0.01
CH4	0.00	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.01	0.02
N2O	0.00	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00	0.04
CO2	1.84	3.27	4.38	0.02	0.02	-	0.09	-	4.51	5.94	15.56

Table A-4: Estimated pre-plant life-cycle energy (Btu/MMBtu output) and emission impacts (lbs/MMBtu) for Residual Oil

	Crude for Use in U.S. Refineries	Refining	Refining: Non-Combustion Emissions	Transportation and Distribution	Storage	**TOTAL**
Total energy	38,266	52,379	-	6,944	-	97,589
Fossil fuels	36,836	51,703	-	6,896	-	95,435
Coal	7,105	9,448	-	276	-	16,829
Natural gas	17,588	16,569	-	721	-	34,878
Petroleum	12,142	25,686	-	5,899	-	43,727
VOC	0.01	0.00	0.00	0.00	-	0.01
CO	0.01	0.00	0.00	0.00	-	0.02
NOx	0.05	0.01	0.00	0.02	-	0.09
PM10	0.00	0.01	0.00	0.00	-	0.01
PM2.5	0.00	0.00	0.00	0.00	-	0.00
SOx	0.02	0.01	0.01	0.01	-	0.04
CH4	0.20	0.01	-	0.00	-	0.21
N2O	0.00	0.00	-	0.00	-	0.00
CO2	8.42	7.78	0.83	1.26	-	18.32

Table A-5: Estimated pre-plant life-cycle energy (Btu/MMBtu output) and emission impacts (lbs/MMBtu) for Natural Gas

	Recovery	Processing	Processing: Non-Combustion Emissions	Transmission and Distribution	TOTAL
Total energy	31,200	31,849	-	8,622	71,949
Fossil fuels	31,096	31,565	-	8,535	71,472
Coal	572	1,397	-	424	2,402
Natural gas	26,803	29,665	-	8,064	64,780
Petroleum	3,721	502	-	46	4,290
VOC	0.00	0.00	0.01	0.00	0.01
CO	0.01	0.00	0.00	0.00	0.02
NOx	0.03	0.01	0.00	0.01	0.05
PM10	0.00	0.00	0.00	0.00	0.00
PM2.5	0.00	0.00	0.00	0.00	0.00
SOx	0.00	0.00	0.02	0.00	0.03
CH4	0.01	0.00	-	0.00	0.43
N2O	0.00	0.00	-	0.00	0.00
CO2	3.86	4.17	2.72	0.68	11.55

Table A-6: Estimated pre-plant life-cycle energy (Btu/MMBtu output) and emission impacts (pounds per MMBtu) for Forest Wood

	machinery	field work	Nitrogen	P2O5	K2O	CaCO3	Herbicide	Insecticide	chemicals	hauling	TOTAL
Total energy	9,938	58,507	-	-	-	-	-	-	-	31,623	100,068
Fossil fuel total	9,521	57,485	-	-	-	-	-	-	-	31,536	98,542
Coal	3,533	5,705	-	-	-	-	-	-	-	862	10,100
Natural gas	5,133	4,159	-	-	-	-	-	-	-	1,656	10,947
Petroleum	855	47,621	-	-	-	-	-	-	-	29,019	77,494
non-fossil fuel	417	1,022	-	-	-	-	-	-	-	87	1,526
VOC	0.00	0.01	-	-	-	-	-	-	-	0.00	0.01
CO	0.02	0.04	-	-	-	-	-	-	-	0.01	0.07
NOx	0.00	0.07	-	-	-	-	-	-	-	0.03	0.10
PM10	0.00	0.01	-	-	-	-	-	-	-	0.00	0.01
PM2.5	0.00	0.01	-	-	-	-	-	-	-	0.00	0.01
SOx	0.00	0.01	-	-	-	-	-	-	-	0.00	0.01
CH4	0.00	0.01	-	-	-	-	-	-	-	0.01	0.02
N2O	0.00	0.00	-	-	-	-	-	-	-	0.00	0.00
CO2	1.84	10.11	-	-	-	-	-	-	-	5.44	17.40