UNIVERSITY OF WISCONSIN—GREEN BAY

HEATING FUEL LIFE-CYCLE ASSESSMENT

Pellet Fuels Institute
1901 North Moore Street, Suite 600
Arlington, VA 22209

February 5, 2007

Mr. Don Kaiser
Executive Director
Pellet Fuels Institute
1901 North Moore Street, Suite 600
Arlington, VA 22209

Re: Heating Fuel Life Cycle Assessment
University of Wisconsin-Green Bay Project 133-JF66

Dear Don:

The attached final report presents a summary of the heating fuel life cycle assessments for heating fuels, including wood pellet fuel, heating oil, natural gas, liquid petroleum gas (LPG) gas, switchgrass, corn, geothermal, and green wood chips. This report was prepared in accordance with the University of Wisconsin-Green Bay's proposal and the objectives outlined in this proposal have been included in this report.

If you have any additional questions, please contact me at 920-465-2278 or katersj@uwgb.edu.

Respectfully,

University of Wisconsin-Green Bay

Dr. John F. Katers
Associate Professor of Natural and Applied Sciences (Engineering)

Joshua Kaurich
Graduate Research Assistant, Environmental Science and Policy

1.0 Executive Summary

Wood pellet fuel processing costs, average net energy ratio, and average fossil energy ratio were estimated and compared to seven other space heating fuels. The seven space heating fuels in addition to wood pellet fuel that were included in the study were as follows: heating oil, natural gas, liquid petroleum gas (LPG), switchgrass, corn, geothermal, and green wood chips. Liquid petroleum gas was determined to have the greatest average net energy ratio of 0.80, while wood chips had the lowest at 0.60. With a net energy ratio of 0.73, wood pellets were ranked just above the average of 0.72 for all fuels considered. Wood pellets had an average fossil energy ratio of 11.5, ranked just above the average at 10.8, second behind green wood chips which had a fossil energy ratio of 31.0 and well above geothermal at 2.5. Wood pellet life-cycle cost was \$2.98 per MMBTU, while the lowest cost of \$2.07 per MMBTU came from green wood chips and the highest cost being geothermal at \$8.97 per MMBTU. The average life-cycle cost for all fuels considered was \$3.85 per MMBTU. Wood pellets were ranked fourth for input energy requirement and wood pellets were found to have consumed less fossil fuel during their life-cycle. Minimal use of fossil fuels and a lower feedstock cost are a few reasons why the wood pellet life-cycle is amongst the most cost effective heating fuel to use, while also having the second highest fossil energy ratio.

Table of Contents

List of Tables

List of Figures

References

Appendix

2.0 Background

A diverse array of fuels are utilized for space heating purposes in Wisconsin. Space heating fuels can be categorized as renewable or non-renewable. As fossil fuel becomes more closely linked to the nations economy and national security, ranking space heating fuels based upon their fossil energy reliance provides insight into the fuels' future security and present weaknesses. A potential method to observe this is by examining each heating fuels fossil energy ratio. The fossil energy ratio is the net energy output divided by the total fossil energy input during extraction, processing, delivery, and utilization. To find the fossil energy ratio, a life-cycle analysis must be performed. Heating fuels examined in this study originate from different sources and follow a variety of energy pathways. Heating oil, natural gas, and liquid petroleum gas may be transported from remote regions of the globe via tanker, rail, and pipeline; while fuel such as corn, wood, and switchgrass may be produced and harvested locally in Wisconsin.

Wisconsin's abundance of timber and wood waste has made wood fuel pellets a competitive and viable space heating option. Wood waste is a substantial and abundant renewable resource that can be used for thermal energy. In 2003, over 1,154 trillion BTUs of biomass were used for thermal outputs (U.S. Department of Energy, 2005b). In Wisconsin, forests cover 16 million acres, or 46% of the states land area and between the years of 1983 to 1996, the average net annual forest growth has exceeded harvest by 158 million cubic feet (Wisconsin Department of Natural Resources, 2004). Despite the wealth of resources, processing costs and net energy values have not been determined for wood fuel pellets. Though overall commodity price may be a vital tool in comparing heating fuels, life-cycle process efficiency and process cost are equally important. The Pellet Fuel Institutes (PFI) has expressed interest in uncovering wood fuel pellets life-cycle process costs and net energy output compared to other space heating fuel options.

This study examined the processing costs, net energy output, and fossil energy ratios for: heating oil, natural gas, liquid petroleum gas (LPG), switchgrass, corn, geothermal, green wood chips, and wood pellet fuel. A functional unit of 1 million Btu (MMBTU) was established as an input energy value. Existing studies, the Department of Energy, the Argonne National Laboratory

Greenhouses gases, Regulated Emissions, and Energy use in Transportation (GREET) Model , as well as personal interviews were utilized in calculating life-cycle costs and energy expenditures. The GREET Model has been used in a host of life-cycle reports, technical papers, and presentations[1]. Life-cycle paths of highest and lowest efficiency were determined for each space heating fuel. Averages taken from the highest and lowest efficiency life-cycles were computed and utilized to make overall comparisons of the process cost, fossil energy ratio, and net energy ratio which can be found in Figure 1 and 2 at the end of this report.

---

[1] A list of publication where the GREET Model has been used can be found at the Argonne National Laboratory website: http://www.transportation.anl.gov/software/GREET/publications.html

3.0 Existing Space Heating Fuels

As mentioned previously, fuels used for space heating come from renewable and non-renewable sources. In addition, heating fuels may be produced and harvested locally in Wisconsin or imported from outside Wisconsin and the United States. Corn, wood fuel pellets, green wood waste, and switchgrass can all be produced in Wisconsin, although it should be noted that switchgrass has only been grown in Wisconsin for experimental purposes. As will be discussed later, switchgrass has been grown in Iowa as a co-firing fuel with coal and is being used in Canada and Europe as an alternative heating fuel option. Heating oil, natural gas, and LP are all imported into Wisconsin, which has no natural reserved of these fossil fuels. The origin of these fuels includes Canada, the Gulf of Mexico, and the Middle East. Lastly, geothermal heat utilizes the ground as a reliable source of thermal energy. However, the power needed to operate the ground source heat pump used in the geothermal system generally comes from the local electric utility. Because of this electrical power requirement, geothermal technology can be considered to be a domestic Wisconsin fuel with a non-renewable energy requirement, provided the heat pump is not operated using photovoltaic panels or other renewable energy technologies for generating electricity.

4.0 Wood Fuel Pellets

Wood fuel pellets can be manufactured from either dry wood waste and other similar materials or green wood waste and similar materials. Dry wood feedstock generally has a moisture content of approximately 5-15%. Dry wood feedstock can generally be obtained from saw mill waste or other similar industries that utilize kiln dried wood. This study assumed that a dry wood feedstock was available and drying the wood was not necessary, which would not be the case for wood fuel pellets manufactured from green wood waste. Green raw materials can often have a moisture content in excess of 60%. Moisture content will depend on time of harvest, relative humidity, as well as type of wood harvested. For this study it was assumed that the wood had a harvested moisture content of 55%. A higher heating value (HHV) of 8,600 BTU per pound of hard wood was established to determine the initial volume of harvested wood needed (Bioenergy Feedstock Information Network, n.d.). It was estimated that 1,115 BTU of energy was needed to vaporize off a pound of water, assuming a heat of vaporization of 40.7 KJ/mole and a specific heat of 4.184 $Jg^{-1}°C^{-1}$. These values were also used in estimating the heat of vaporization for corn, switchgrass, and green wood waste. An average moisture content of 8% for finished wood pellets was used based upon information obtained from the department of energy (U.S. DOE, 2005c).

For the most efficient life-cycle, the process begins with the initial pick-up of the dry feedstock at the generator. Therefore, transportation energy expenditures only account for single direction transport and not round trip. Transportation costs are based upon a Midwest diesel fuel price of $2.56 per gallon (U.S. DOE, 2006d) with an energy value of 138,690 BTU (U.S. DOE, 2005). The average distance that the feedstock was transported to the plant was 137.4 miles, while the average distance that the final product was transported was 195 miles[2]. A fuel economy of 5 mpg was chosen as a standard for the transporting vehicles. Plant energy requirements shown in Table 1 were taken from personal interviews with two pellet fuel companies. Pellet mill operations account for the second greatest energy expenditure and cost for both life-cycles. Industrial facility pellet mill operation expenses were assumed to be $.0578 per kW-hr (U.S.

---

[2] Information taken from personal interviews with five wood pellet fuel companies.

DOE, 2006e). Plant operations include the power for lighting, conveyers, packaging equipment, cooling fans, and hammer mill operation.

Stove efficiency during product end use actually has the greatest effect on the net energy output. The vaporization of water occurs during the combustion of the fuel, where energy from the dry wood pellets is expended to drive off water. Based upon information from the Pellet Fuel Institute, a fuel cost of $165 per ton was used calculate process cost associated with water vaporization and combustion. Based upon information from the Department of Energy, pellet stove combustion efficiency ranges from 78% to 85% (U.S. DOE, 2005a). As noted previously as well as in Table 1, combustion efficiency has the most substantial affect on the overall cost and net energy output.

Three differences exist between the most efficient cycle and the least efficient cycle for wood fuel pellets. Harvesting, chipping, and drying of feedstock are included within the least efficient life-cycle. Harvesting and loading includes site preparation, planting, growing, harvesting and loading of timber into the wood chipper (Comnick, Johnson, Lippke & Marshall, 2005; Puettmann & Wilson, 2005). For chipping, it was assumed that a 500 HP chipper with an output of 50 tons of scrap wood per hour would be utilized. Harvesting, chipping, and drying account for minimal process cost. However, drying accounts for the second greatest energy requirement of the least-efficient cycle. If the pellet mill purchases wood feedstock at $20/ton, a drying cost of $0.11 per MMBTU can be calculated for the least-efficient cycle assuming the purchased feedstock is used to dry the product (Bi, Mani, Sokhansanj & Turhollow, 2006). A combustion efficiency of 78% accounts for a process cost of $1.91.

Transportation of wood fuel pellets purchased and transported from retailer to consumer were not figured in this life-cycle, as these costs and energy expenditures were assumed to be minimal in the overall life-cycle totals and were thus assumed to be negligible. A summary of the analysis for wood pellet fuel can be seen in Table 1.

Table 1 - Wood Pellets

Most Efficient Life-Cycle

	Energy Input	1 Transporting Feedstock to Plant	2 Plant Operations	3 Transporting final Product	4 Water Vaporization at 8% Moisture	5 Combustion	Totals	Net Energy Output	6 Net Energy Ratio	7 Fossil Energy Ratio
Total BTU Remaining	1,000,000	987,249	957,488	943,755	924,219	785,586		785,586	0.79	14
Total BTUs Required	0	12,751	29,760	13,733	19,535	138,632	214,411			
Fossil BTUs Required	0	12,751	29,760	13,733	0	0	56,244			
Process Efficiency (%)	100%	98.72%	96.99%	98.57%	97.93%	85.00%	78.56%			
Process Cost	0	$0.24	$0.51	$0.26	$0.20	$1.41	$2.66			

Least Efficient Life-Cycle

	Energy Input	Harvesting and Loading	8 Chipping Feedstock	Transporting Feedstock to Plant	9 Drying (55% to 12%)	Plant Operations	Transporting Final Product	Water Vaporization at 8% Moisture	Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	981,496	978,933	966,403	905,811	878,546	866,279	848,350	661,713		661,713	0.66	9
Total BTUs Required	0	18,504	2,563	12,530	60,592	27,265	12,567	17,929	186,637	338,587			
Fossil BTUs Required	0	18,504	2,563	12,530	0	27,265	12,567	0	0	73,429			
Process Efficiency (%)	100%	98.15%	99.74%	98.72%	93.73%	96.99%	98.57%	97.93%	78.00%	66.15%			
Process Cost	0	$0.15	$0.05	$0.24	$0.11	$0.46	$0.23	$0.18	$1.91	$3.33			

Sources:

1
Transportation energy Data - Department of Energy
Transportation Data - Personal interviews with 5 pellet fuel companies

2
Operations Data - from interviews with 2 pellet fuel companies
Process cost Data - Department of Energy ($.0578 per kW-hr)

3
Shipping Data - from interviews with 5 pellet fuel companies
Transportation energy Data - Department of Energy

5
Fuel cost Data - $165 per ton (Pellet Fuel Institute)
Combustion efficiency Data - Dept. of Energy

Notes:

4
Assume an energy expenditure of 1115 Btu per lb. water

6
Net energy ratio = net energy output/ energy input

7
Fossil energy ratio =net energy output/ fossil energy used

8
Assume 500 HP Hammer Mill at 50 tons per hour output

9
Assume $20 per ton cost of feedstock
Assume product is dried from companies own feedstock

5.0 Green Wood Chips

Wood waste is a substantial and abundant renewable resource that can be used for electricity and thermal energy production. The most efficient method of harvesting timber is to clear cut and harvest from pre-existing stands. In clear cutting, all trees in a stand are removed and the entire tree can be used for chipping. A HHV of 8,600 BTU per pound for hard wood was established to determine the initial volume of harvested wood needed (Bioenergy, n.d.). The most efficient life-cycle found in Table 2 displays the energy and cost associated with clear cut harvesting and loading of green wood waste, with harvesting displayed as *felling and yarding* of timber. Energy inputs associated with felling, yarding, and loading of harvested trees were obtained from a life-cycle impact study of forest resource activities in the Pacific Northwest and assumed to be similar for Midwest harvesting (Comnick, 2005). Process costs were based upon a diesel price of \$2.56 per gallon. For chipping, it was assumed that a 500 HP chipper with an output of 50 tons of scrap wood per hour would be utilized. From Table 2, it can be seen that the energy expenditures associated with chipping are 2,590 BTU's per MMBTU with a process cost of \$0.05 per MMBTU input. Rail transportation energy requirements were estimated at 24 BTU per cubic foot mile (Puettmann, 2005). A 200 mile rail transport results in an energy expenditure of 4,722 BTU for the most efficient cycle. Wood vaporization was calculated for green wood feedstock with 55% w/w moisture content to dry wood. Water vaporization expends 70,245 BTUs of energy per MMBTU and accounts for the second greatest process cost in both the least and most efficient cycle. A maximum efficiency of 75% was set for commercial green wood waste boilers (Maker, 2004). Process costs associated with combustion and water vaporization were based on a fuel cost of \$50 per ton for hard wood. Low combustion efficiency accounts for the greatest cost and energy expense through both life-cycles. The final result of the most-efficient system is a net energy ratio of 0.69 and a fossil energy ratio of 45.

For the least efficient cycle we assume added energy values for land that needs to be prepared for planting, as well as the planting and maintenance of harvest. In addition, on road transportation was added to the least efficient cycle in instances where businesses are not located near rail lines. An on-road travel distance of 25 miles with a 20 ton load was assumed and energy expenditures were calculated based upon a tractor trailer fuel economy of 5 mpg with diesel energy values of 138,690 BTU per gallon. A low value of 55% efficiency was set for commercial wood boilers (Maker, 2004). Clearly, a substantial loss of energy and process cost is due to an inefficient boiler system. Table 2 displays a loss of over 405,000 BTU during combustion in the least efficient cycle.

Table 2 - Green Wood Chips

Most Efficient Life-Cycle

	1 Energy Input	2 Clear Cut Felling	3 Clear Cut Yarding	4 Loading	5 Chipping Feedstock	6 Rail Transport	7 Water Vaporization at 55% Moisture	8 Combustion	Totals	Net Energy Output	9 Net Energy Ratio	10 Fossil Energy Ratio
Total BTU Remaining	1,000,000	999,660	994,593	992,136	989,546	984,824	914,579	685,934		685,934	0.69	45
Total BTUs Required	0	340	5,067	2,457	2,590	4,722	70,245	228,645	314,066			
Fossil BTUs Required	0	340	5,067	2,457	2,590	4,722	0	0	15,176			
Process Efficiency (%)	100%	99.97%	99.49%	99.75%	99.74%	99.52%	92.87%	75.00%	68.59%			
Process Cost	0	$0.01	$0.09	$0.05	$0.05	$0.09	$0.32	$1.03	$1.64			

Least Efficient Life-Cycle

	Energy Input	11 Site Prep., Planting, Growing, Harvesting	12 Loading	Chipping Feedstock	Rail Transport	13 On-road Transport	Water Vaporization at 55% Moisture	14 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	988,542	981,625	979,063	974,391	971,357	902,091	496,150		496,150	0.50	17
Total BTUs Required	0	11,458	6,917	2,563	4,672	3,034	69,266	405,941	503,851			
Fossil BTUs Required	0	11,458	6,917	2,563	4,672	3,034	0	0	28,644			
Process Efficiency (%)	100%	98.85%	99.30%	99.74%	99.52%	99.69%	92.87%	55.00%	49.61%			
Process Cost	0	$0.02	$0.13	$0.05	$0.09	$0.06	$0.32	$1.83	$2.50			

Sources:

1,2,3,4,6,11,12

Harvest Data - From two studies by Wood and Fiber Science Magazine, Corrim Special Issue

8,14

Combustion efficiency Data - Biomass Energy Resource Center

Notes:

5

Assume 500 HP Hammer Mill at 50 tons per hour

7

Assume an energy expenditure of 1115 Btu per lb. water

9

Net energy ratio = net energy output/ energy input

10

Fossil energy ratio =net energy output/ fossil energy used

13

Assume 25 mile travel distance

Process cost Data - Department of Energy ($2.56 gallon; diesel)

6.0 Corn

Corn represents another domestic option for space heating purposes. Based on a 2002 census by the United States Department of Agriculture (USDA), corn used for silage purposes in Wisconsin totaled 704,513 acres, which ranked Wisconsin first in the United States. In addition, corn used for grain totaled 2,862,031 acres and ranked Wisconsin eighth in the U.S. (U.S. Department of Agriculture, 2002). Despite its use for animal feed, corn can also be utilized as a heating fuel. For home heating purposes, corn kernels can be burned in stoves similar to pellet stoves. In many cases, pellet stoves are already equipped to handle corn as well as wood fuel pellets. However, corn must have moisture content lower than 15% for optimal burn efficiency (Spieser, 1993). Not all shelled corn harvested falls below a 15% moisture content. In many cases, the corn kernels must be dried before they are used for home heating purposes. A HHV of 8,250 BTU per pound (Penn State University, 2003) for shelled corn was used to determine the initial crop size needed from a harvested kernel at 22% and 30% moisture content for the most and least efficient cycles, respectively. According to the USDA Commodity Insurance Fact Sheet, from 1995 to 2005 Wisconsin averages 130 bushels of corn per acre (U.S.D.A., 2005). This results in a harvest of 155.4 pounds of corn at 22% moisture for the most efficient life-cycle and a harvest of 173.2 pounds of corn at 30% moisture for the least efficient cycle. Based upon two ethanol life-cycle analysis conducted by the USDA, planting and harvesting of an acre of corn in Wisconsin consumes 8.5 gallons of diesel fuel (Duffield, Shapouri & Wang, 2002; Duffield, Graboski & Shapouri, 1995). The result is an energy expenditure of 23,212 BTU per 1 MMBTU of corn kernel harvested at a cost of $0.43 for the most-efficient cycle and 24,167 BTU expended at a cost of $0.45 considering a cost of diesel fuel to be $2.56 a gallon.

Typically corn has moisture content when harvested of 20-22% (Maier & Uhrig, 1992). However, depending on the season and outdoor weather conditions, corn may be harvested with moisture content as high as 30%. For optimal combustion, the corn kernels must be dried to a moisture content of 15%. As a result, drying corn results in the expenditure of 31,498 BTUs of energy when dried from 22% moisture to 15% moisture using a natural gas boiler (Maier et al., 1992). The net cost of drying with natural gas is $0.39 for the most efficient cycle based upon a natural gas cost of $12.79 per thousand cubic feet (U.S. DOE, 2006c). Assuming an electric dryer is used in the least efficient cycle, drying corn from 30% to 15% moisture, at a cost of $0.0999 per kW-hr (U.S. DOE, 2006e), results in the expenditure of 59,743 BTUs of energy at a cost of $1.75 (Maier et at., 1992). Table 3 shows that drying results in the second greatest life-cycle cost with both an electric and natural gas dryer.

Similar to burning pellets and green wood, energy is lost during the combustion of corn due to stove inefficiency as well as moisture vaporization. As stated earlier, 1115 BTU of energy is needed to vaporize 1 pound of water. In the most efficient life-cycle combustion, vaporization account for over 80% of the total energy expended. Combustion costs for the most efficient cycle are calculated by assuming a corn fuel cost of $2.50 per bushel (Wisconsin Ag Connection, 2006). A cost of $3.61 per bushel was established for corn used in the least efficient cycle based upon December values from the Chicago Board of Trade (2006). Corn kernel stoves have a range of 65-75% efficiency (Penn, 2002). It is evident that combustion of corn accounts for the greatest energy expenditure and cost throughout both the least and most efficient life-cycles.

Transportation costs and energy expenditures for delivery of corn fuel from the producer to the consumer are not figured into the life-cycle. In many cases, companies that sell corn stoves organize a local fuel supplier (farmer) for the consumer. Therefore, it was assume that the producer and fuel supplier will be located within close proximity of each other and that travel expenses and energy costs will be negligible. A summary of the analysis for corn can be seen in Table 3.

Table 3 - Corn

Most Efficient Life-Cycle

	Energy Input	1 Corn Establishment, Fertilization, and Harvest	2 Drying With Natural Gas (22% to 15%)	3 Water Vaporization at 15% Moisture	4 Combustion	Totals	Net Energy Output	5 Net Energy Ratio	6 Fossil Energy Ratio
Total BTU Remaining	1,000,000	976,788	945,290	922,745	692,059		692,059	0.69	13
Total BTUs Required	0	23,212	31,498	22,545	230,686	307,941			
Fossil BTUs Required	0	23,212	31,498	0	0	54,710			
Process Efficiency (%)	100%	97.68%	96.78%	97.62%	75.00%	69.21%			
Process Cost	0	$0.43	$0.39	$0.14	$1.48	$2.44			

Least Efficient Life-Cycle

	Energy Input	Corn Establishment, Fertilization, and Harvest	7 Drying With Electricity (30% to 15%)	Water Vaporization at 15% Moisture	8 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	975,833	916,090	894,236	581,253		581,253	0.58	7
Total BTUs Required	0	24,167	59,743	21,854	312,983	418,747			
Fossil BTUs Required	0	24,167	59,743	0	0	83,910			
Process Efficiency (%)	100%	97.58%	93.88%	97.61%	65.00%	58.12%			
Process Cost	0	$0.45	$1.75	$0.20	$2.90	$5.30			

Sources:

1

Planting and harvesting Data - Department of Agriculture

2

Drying Data - Agricultural harvest study, Purdue University

Process cost Data - Department of Energy ($12.79 per 1000 cu. Ft.)

4

Combustion Data - Penn State University

Fuel cost Data - Wisconsin Ag Connection ($2.50 bushel)

7

Process cost Data - Department of Energy ($.0999 kW-hr.)

8

Fuel cost Data - National Corn Growers Association ($3.61)

Notes:

3

Assume an energy expenditure of 1115 Btu per lb. water

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

7.0 Switchgrass

The use of switchgrass (*panicum virgatum*) as a space heating fuel has not been implemented yet in Wisconsin. However, switchgrass has been harvested and incinerated as a supplementary fuel in coal power plants. For example, in Iowa, switchgrass has been co-fired by Alliant Energy in their Ottumwa Generating Station (Chariton Valley Biomass Project, 2006). For use as a home space heating fuel, switchgrass must be harvested, bailed, and sent through a hammer mill similar to wood pellet fuels before being pelletized. Currently, extensive studies are being conducted by the independent non-profit organization group known as the Resource Efficient Agriculture Production (R.E.A.P.) Canada team. R.E.A.P.-Canada has created several studies to test the feasibility of pelletized switchgrass for home or business heating purposes. This study will examine the life-cycle of switchgrass as though it was harvested in Wisconsin, with assumptions based upon information taken from R.E.A.P.-Canada and the Chariton Valley Biomass Project.

Switchgrass establishment, fertilizer application, and harvesting data was taken from a study conducted by R.E.A.P.-Canada. Energy expenditures for these steps total 50,319 BTU assuming a HHV value of 7,200 BTU per pound for switchgrass (U.S.D.A., 2004). The costs associated with switchgrass establishment, fertilizing, and harvesting were calculated by assuming a diesel expense of $2.56 per gallon.

Transportation vehicle fuel economy was set at 5 mpg. Based upon an average switchgrass cargo weight of 14.0 tons per truckload (Daly, Graham, Noon & Zahn, 1996), Table 4 shows a costs $0.01 to transport 949,681 BTUs of switchgrass 5 miles, as seen in the most efficient cycle, and $0.13 to transport switchgrass 50 miles in the least efficient cycle.

Pellet mill operational costs and energy expenditures were calculated from two studies done by R.E.A.P.-Canada. Pellet mill operations include hammer mill operation, pelletizing, conveyers, lighting, cooling fans, and material packaging equipment (Samson et al., 2000). An average industrial energy cost of $0.0578 per kW-hr was assumed for a switchgrass pellet facility (U.S.

DOE, 2006e). A study by R.E.A.P.-Canada found that switchgrass with moisture content less than 14.5% can be pelletized without prior drying. Most switchgrass is harvested with moisture content between 12% and 20% (Samson et al., 2000). For the least efficient switchgrass life-cycle, it was assume that the switchgrass must be dried from 20% moisture to 14.5% moisture for pelletization. Cost for drying in the least-efficient cycle was $0.04, assuming a $50 a ton feedstock cost based upon data taken by the Chariton Valley Biomass Project (2005).

For transporting the final product, it was assumed that transporting distance, fuel economy, and shipping volume were similar to wood fuel pellet transportation. With this assumption, the transporting distance is 195 miles with a truck fuel economy of 5 mpg, and a hauling load of 22.82 tons of product. Final transportation of product results in the fourth greatest expense in both life-cycles.

Assuming an energy expenditure of 1115 BTU for each pound of water vaporized; 13,980 BTU of energy are needed to vaporize the water in the most-efficient cycle and 11,720 BTU in the least-efficient cycle. The cost of vaporization and combustion is based upon a $186 a ton price for delivered switchgrass pellets purchased by the consumer (Forest, 2004). Combustion efficiency data was taken from R.E.A.P.-Canada, with an efficiency range between 81% and 87% (Drisdelle, Duxbury, Lapointe, Mulkins & Samson, n.d.). From Table 4 we see combustion costs are $1.52 and $2.17 at 87 and 81% efficiency, respectively. Overall, little variation in net and fossil energy ratio exists between the most and least efficient cycle.

Table 4 - Switchgrass

Most Efficient Life-Cycle

		1	2	3		4	5			6	7
	Energy Input	Switchgrass Establishment, Fertilization, Harvest	Transportation (5 miles)	Pellet Mill Operations	Transporting final Product	Water Vaporization at 9% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	949,681	949,016	926,999	913,743	899,763	782,793		782,793	0.78	9
Total BTUs Required	0	50,319	665	22,017	13,256	13,980	116,970	217,207			
Fossil BTUs Required	0	50,319	665	22,017	13,256	0	0	86,257			
Process Efficiency (%)	100%	94.97%	99.93%	97.68%	98.57%	98.47%	87.00%	78.28%			
Process Cost	0	$0.93	$0.01	$0.37	$0.25	$0.18	$1.52	$3.26			

Least Efficient Life-Cycle

			8	9				10				
	Energy Input	Switchgrass Establishment, Fertilization, Harvest	Transportation (50 miles)	Drying (20% moisture to 14.5%)	Pellet Mill Operations	Transporting final Product	Water Vaporization at 9% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	949,681	942,653	930,909	909,777	896,767	883,047	715,268		715,268	0.72	8
Total BTUs Required	0	50,319	7,027	11,744	21,131	13,009	13,720	167,779	284,729			
Fossil BTUs Required	0	50,319	7,027	0	21,131	13,009	0	0	91,486			
Process Efficiency (%)	100%	94.97%	99.26%	98.76%	97.73%	98.57%	89.73%	81.00%	65.18%			
Process Cost	0	$0.93	$0.11	$0.04	$0.37	$0.24	$0.18	$2.17	$4.04			

Sources:

1

Switchgrass Data - R.E.A.P. - Canada

Process cost Data - Department of Energy ($2.56 gallon; diesel)

3

Pellet mill Data - taken from 2 studies completed by R.E.A.P. - Canada

Process cost Data - Department of Energy ($.0578 per kW-hr)

5,10

Fuel cost Data - Forest Products Laboratory ($186 per dry ton)

Efficiency Data - R.E.A.P. Canada

Notes:

2,8

Assuming variable distance from harvest region

5,9

Assume an energy expenditure of 1115 Btu per lb. water

6

Net energy ratio = net energy output/ energy input

7

Fossil energy ratio =net energy output/ fossil energy used

9

Feedstock price - assume $50 per ton

8.0 Geothermal

In Wisconsin, geothermal systems are utilized to meet heating, cooling, and hot water demands for residential homes and businesses. In 2003, one-third of all geothermal heat pumps were being shipped to the Midwest for installation (U.S. DOE, 2005b). Geothermal technology has expansive possibilities for home heating in Wisconsin. However, the heat pumps used in the geothermal systems are generally powered by the local electric utility, which puts its process cost substantially above other space heating fuels.

In considering operation cost, a price of $0.0999 per kW-hr for a residential customer was used (U.S. DOE, 2006e). Table 4 displays the four main components of a geothermal system. These components include a compressor, fan, and an external and internal pump. Geothermal systems are rated based upon their Coefficient of Performance (COP). The COP of a geothermal system is found by taking output energy and dividing it by total process energy. The Econar Geosource 2000 GV/GH 520/521 system, the Climate Master Traquility, and the WaterFurnace Premiere P40 systems were chosen to examine life-cycle energy expenditures and costs. These three systems are the most current versions of geothermal systems installed in residential homes in Wisconsin. An average entering water temperature of 50° Fahrenheit[3] is used in the COP calculations. The average COP for the three systems chosen under these parameters is 4.33. From Table 5, the result was an expenditure of 230,946 BTU per 1 MMBTU output of energy. This results in an operation cost of $6.69 per MBTU.

For the least efficient life-cycle, the lowest *Energy Star* COP rating for a geothermal system was selected. A COP of 2.8 was chosen as a baseline for a modern geothermal system (U.S. DOE, 2005b). Table 5 shows that with a low efficiency geothermal system, 357,143 BTUs of energy is expended for each 1 MMBTU input of energy. The result is an operation cost of $11.24 per MMBTU.

---

[3] Information based upon personal interviews with two Wisconsin geothermal sales companies.

It can be seen in Table 5 that the net energy ratio and fossil energy ratio are directly affected by the COP of the system chosen. Process costs also fluctuate based upon electric utility prices. Few options exist for lowering operation costs. However, process costs could be decreased if alternative energy supplies such as photovoltaic power are used in place of on-grid utility supplied power. It should be noted that the use of renewable energy as a power supply would result in a higher fossil energy ratio, but would require much larger capital investments.

Table 5 - Geothermal

Most Efficient Life-Cycle

	Energy Input	1 Compressor, Fan, External, Internal Pump	Totals	Net Energy Output	3 **Net Energy Ratio**	4 **Fossil Energy Ratio**
Total BTU Remaining	1,000,000	769,054		769,054	0.77	3
Total BTUs Required	0	230,946	230,946			
Fossil BTUs Required	0	230,946	230,946			
Process Efficiency (%)	100%	71.65%	71.65%			
Process Cost	0	$6.69	$6.69			

Least Efficient Life-Cycle

	Energy Input	5 Compressor, Fan, External, Internal Pump	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	642,857		642,857	0.64	2
Total BTUs Required	0	357,143	357,143			
Fossil BTUs Required	0	357,143	357,143			
Process Efficiency (%)	100%	64.29%	64.29%			
Process Cost	0	$11.24	$11.24			

Sources:
1
Compressor, fan, pump data - Specification catalogs of 3 geothermal manufacturers
5
Compressor, fan, pump Data - Department of Energy
Process cost Data - Department of Energy ($0.0999 kW-hr)

Notes:
3
Net energy ratio = net energy output/ energy input
4
Fossil energy ratio =net energy output/ fossil energy used
5
Assume a 2.8 coefficiency of performance

9.0 Heating Oil

Many businesses and home have relied upon heating oil to meet their thermal energy demands. However, all of Wisconsin's heating oil is imported from a vast array of locations. In 2005, Wisconsin consumed 61.6 million gallons of petroleum for residential purposes. Of this amount, 506,106 gallons were off-road distillate used for home heating purposes, with small amounts used for aviation fuel (Wisconsin, 2006). Most oil used in Wisconsin is obtained from Alberta Canada, Texas, Oklahoma, and from the Gulf of Mexico. Oil that enters the Gulf is acquired ubiquitously throughout the world. In this study, expenses for transporting crude oil via tanker was considered unsubstantial with no effect on the overall life-cycle and is not factored in this analysis.

In table 6, the most efficient life-cycle has an extraction efficiency of 98% (Argonne, 2005) with costs of $0.13 per MMBTU. One of the least efficient ways to extract crude oil is from bitumen oil sands. As mentioned earlier, much of the crude obtained from Canada is extracted from Bitumen oil sands. Approximately 35,000 thousand barrels of oil were imported from Canada to the Midwest in August of 2006 (U.S., 2006b). Extraction from bitumen rock is 94.8% efficient and costs $0.39 per MMBTU. Natural gas accounts for 80% of the energy used for extraction, while electricity and petroleum accounts for 10% each (California Energy Commission, 2006). These values and percentages were assumed similar in all areas where extraction is done. In order to calculate extraction costs, the cost of electricity is assumed to be $0.0578 per kW-hr (U.S. DOE, 2006e), crude oil is assumed to have a well head price of $8.66 per MMBTU, and natural gas well head price is assumed to be $6.33 per MMBTU (U.S. DOE, 2006a).

As seen in Table 6, refining of crude oil consumes the greatest amount of energy. Refining conventional heating oil (#2 diesel) has an efficiency of 89.5% and costs $1.32 in the most efficient cycle and $1.28 in the least efficient cycle. In 2006, the Marathon Oil Refinery in Superior reported a refining efficiency value of 92.4%[4]. When compared to the 89.5% efficiency

---

[4] Information based upon a personal conversation with Dave Podratz, Refinery Manager for Marathon Oil in Superior.

provided by the GREET Model, a difference of 3.2% is discovered for this step. At the Marathon Oil refinery, the total energy input to refine a barrel of crude oil is 0.422 MMBTU. Of this total 0.067 MMBTU comes from natural gas, 0.279 MMBTU comes from the crude that enters the plant, and 0.077 MMBTU comes from purchased electricity[12]**.** These values were used to compute overall refining costs.

During pipe transportation, most oil enters the Midwest via the Buckeye Pipeline from the east, Magellan pipeline from the south, or the Enbridge Pipeline from western Canada. Once the heating oil enters Wisconsin there are several connecting pipelines used to distribute oil to the jobbers. 10% of the tariff placed on the transported oil goes into pumping of the finished product[5]. The tariff from Edmonton, Canada, to Chicago, Illinois, is $1.75 per barrel. This is equivalent to a transporting cost of $0.03 per MMBTU oil. Assuming electricity powered pumps are used to move the oil, an energy expenditure of 1,556 BTU is noticed in Table 8 for the most efficient cycle and 1,504 for the least efficient cycle.

Jobbers are individuals who transport heating fuel from the terminal station to the retail seller. The average distance that a jobber transports product is 58 miles with an average fuel transporting capacity of 6,980 gallons[6]. Assuming an average fuel economy of 5.8 mpg[14], jobber transport efficiency is at 99.85% with an average hauling cost of $0.03 per 1 MMBTU. Jobber transportation is the lowest BTU input into for life-cycle as heating fuel is transported in large quantities in relatively short distances. Retail transportation is similar to jobber transportation. Retail transportation is the transporting of heating fuel from localized retail sellers to consumers homes. The average radius of transport for retail shipment is 19.3 miles with an average transporting load per household of 275 gallons[7]. Assuming an average fuel economy of 8.3 mpg, Table 6 shows that retail transportation consumes 8,041 BTU per MMBTU for the most efficient cycle and 7,780 BTU per MMBTU for the least efficient cycle. The costs of

---

[5] Information taken from a personal interview with Mitch Jones, Manager of Tariffs and Regulatory Affairs for BP.
[6] Information taken from personal interviews with 5 transporting jobbers in Wisconsin.
[7] Information taken from person interviews with 7 retail transporters in Wisconsin.

transportation are calculated by assuming a price of diesel fuel to be $2.56 per gallon (U.S. DOE, 2006d).

Combustion of heating oil constitutes one of the greatest costs and energy expenditures in the heating fuel life-cycle. Combustion efficiency is calculated by dividing the usable output energy by the available input potential energy. The most efficient heating oil furnace is the condensing oil furnace at 95% efficiency according to the annual fuel utilization efficiency (AFUE) standards (US EPA, 2007). Considering a consumer cost of $15.60 per MMBTU for heating oil (Wisconsin, 2006), the process cost at 95% efficiency is $0.68 in the most efficient cycle and $2.87 in the least efficient cycle.

Most Efficient Life-Cycle

	Energy Input	1 Extraction from Oil Reservoir	2 Refining	3 Pipe Transport	4 Jobber Transport	5 Retail Transport	6 Combustion	Totals	Net Energy Output	7 Net Energy Ratio	8 Fossil Energy Ratio
Total BTU Remaining	1,000,000	980,000	877,100	875,544	874,231	866,190	822,881		822,881	0.82	6
Total BTUs Required	0	20,000	102,900	1,556	1,313	8,041	43,310	177,120			
Fossil BTUs Required	0	20,000	102,900	1,556	1,313	8,041	0	133,810			
Process Efficiency (%)	100%	98.00%	89.50%	99.82%	99.85%	99.08%	95.00%	82.29%			
Process Cost	0	$0.13	$1.32	$0.03	$0.03	$0.14	$0.68	$2.33			

Least Efficient Life-Cycle

	Energy Input	9 Extraction from Bitumen Sands	Refining	Pipe Transport	Jobber Transport	Retail transport	10 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	948,000	848,460	846,956	845,686	837,906	653,766		653,766	0.65	4
Total BTUs Required	0	52,000	99,540	1,504	1,270	7,780	184,140	346,234			
Fossil BTUs Required	0	52,000	99,540	1,504	1,270	7,780	0	162,094			
Process Efficiency (%)	100%	94.80%	89.50%	99.82%	99.85%	99.08%	78.00%	65.38%			
Process Cost	0	$0.39	$1.28	$0.03	$0.03	$0.14	$2.87	$4.74			

Sources:

1,9

Energy Data - Argonne GREET 1.6 Model

Process cost Data - California Energy Commission

2

Process energy and cost Data - Personal Interview with Murphy Oil Refinery

3

Transport energy Data - Embridge Energy Limited Partnership

Transport energy Cost - Personal interview with BP tariff regulatory manager

4,5

Energy Data - Personal interviews with fuel transporters in Wisconsin

6,10

Furnace efficiency Data - Department of Energy
- US EPA (Energy Star)

Notes:

7

Net energy ratio = net energy output/ energy input

8

Fossil energy ratio =net energy output/ fossil energy used

10.0 Natural Gas

Natural gas is extracted from underground reserves or during the extraction of petroleum. Extraction of natural gas from petroleum reservoirs is a more difficult medians and known as unconventional extraction. However natural gas is obtained; all natural gas used in Wisconsin is imported. In 2005, Wisconsin residents used 131.7 trillion BTU of natural gas. This value represents roughly one-third of all the natural gas used in Wisconsin (Wisconsin Department of Administration, 2006). There are many supply sources of natural gas used in Wisconsin. The majority of natural gas is brought into Wisconsin from three main sources. First, natural gas is moved into Wisconsin via the ANR pipeline from Oklahoma, the ANR pipeline from the Gulf of Mexico, and finally via the Great Lakes and Viking supply line that connects to the TransCanada pipeline at the Canadian border. The principal component of natural gas is methane, but other hydrocarbons of propane and butane may be present as well.

The life-cycle of natural gas consists of four components; extraction, refining, transportation, and combustion. As seen in Table 7, natural gas can be extracted from underground reservoirs, or it can be unconventionally extracted from petroleum reserves. Natural gas from Canada may come from petroleum reservoirs found within the bitumen oil sands, while natural gas that comes from the Gulf of Mexico or Oklahoma may be extracted from available underground deposits. Additional energy is needed to extract natural gas from bitumen rock as it must first be separated from heavier petroleum hydrocarbon compounds. The GREET Model was used to determine extraction efficiencies for natural gas removal. An assumption was made that the fuels used to extract natural gas are similar to the fuels used to extract petroleum. It was estimated that 80% of the input energy comes from natural gas itself, 10% from electricity, and the final 10% from petroleum (California, 2006). Table 7 shows the costs to be $0.22 for extraction from natural gas reserves and $0.39 for extraction from bitumen rock.

Natural gas refining and processing involves several steps. First, oil and water is removed from the collected natural gas. Next, contaminates such as hydrogen sulfide and carbon dioxide are removed. In some cases, nitrogen is extracted from the natural gas before it enters the pipeline for transportation (U.S. DOE, 2006g). The GREET Model was used to calculate refining energy expenditures. Natural gas refining from available deposits is 97.2% efficient (Argonne National Laboratory, 2005). The more intensive refining and distillation of natural gas from bitumen oil sands was calculated from the GREET Model by averaging the refining and distillation efficiencies of all several major refining products: conventional gas, liquid petroleum, napthla, residual oil, and diesel fuel. Averages of these refining and distillations were done as natural gas recovered from bitumen sands is similar in energy intensity as refining crude oil (Canadian Association of Petroleum Producers, n.d.). The overall refining and distillation efficiency of natural gas was than calculated to be 91.1% as seen in Table 7. Refining costs were calculated based upon information supplied by Marathon Oil of Superior, Wisconsin[8]. In order to quantify the cost of refining natural gas, we assume the needed energy is similar to that of petroleum. Quantifying energy costs will be described in section 11.0. From Table 7, refining costs are $0.35 for the most efficient life-cycle and $1.10 for the least efficient life-cycle. The increase in energy values and cost between the most and least efficient life-cycle demonstrates the significance of using easily obtainable natural gas reserves over extraction from petroleum beds.

Natural gas is transported to Wisconsin via pipeline. Transportation costs for pipeline shipment were calculated from the ANR Pipeline Company. Transporting cost through the ANR pipeline are based upon Federal Energy Regulatory Commission (FERC) gas tariffs. The *Transporters Use Percentage* for natural gas from the Gulf of Mexico to the Midwest is 2.35% and from Oklahoma to the Midwest is 4.48% (ANR Pipeline Company, 2006). Transporters Use Percentage represents a cost and energy percentage needed to move the total product. Assuming ANR purchases the natural gas to move the product at a wellhead price of $6.51 per thousand cu. Ft. (U.S. DOE, 2006c), it will cost $0.14 to transport NG from the Gulf of Mexico to the Midwest and $0.24 to transport natural gas from Oklahoma to the Midwest. Pressure used to

---

[8] Information based upon a personal conversation with Dave Podratz, Refinery Manager for Marathon Oil in Superior.

move the natural gas through larger main pipes is sufficient enough for it to reach residence and businesses at a usable level, thus further transportation costs are not seen[9].

The final process step for natural gas is combustion. Combustion efficiency for natural gas burners can range from a minimum of 78% to a high of 97% (U.S. DOE, 2006). Furnace efficiency in the natural gas life-cycle accounts for the greatest cost, and by far the most substantial energy requirement in the least efficient cycle as seen in Table 7. The cost with a 97% efficiency furnace is $0.35, while the cost with a 78% efficiency furnace is $2.26 providing a cost of $12.79 per 1000 cu. Ft. for natural gas in Wisconsin (U.S. DOE, 2006c).

A great portion of the costs and energy expended during the life-cycle of natural gas comes from the refining and combustion process. Natural gas that is acquired from easily obtainable underground reservoirs can significantly decrease refining cost as well as the extraction costs. Lowering these values will increase the overall net energy output. Finally, utilizing a high-efficiency furnace is the most crucial improvement to raising the net energy output. The combustion cost of a 78% efficient furnace is roughly $2.00 more than a 97% efficient furnace.

---

[9] Information based upon a personal interview with John Place, manager of planning, engineering, and mapping for WE Energies of Wisconsin.

Table 7 - Natural Gas

Most Efficient Life-Cycle

	Energy Input	1 Extraction from NG Reserve	2 Refining and Distillation	3 Pipeline Transportation (gulf to Wisc.)	4 Combustion	Totals	Net Energy Output	5 Net Energy Ratio	6 Fossil Energy Ratio
Total BTU Remaining	1,000,000	972,000	944,784	922,582	894,905		894,905	0.89	12
Total BTUs Required	0	28,000	27,216	22,202	27,678	105,096			
Fossil BTUs Required	0	28,000	27,216	22,202	0	77,418			
Process Efficiency (%)	100%	97.20%	97.20%	97.65%	97.00%	89.49%			
Process Cost	0	$0.22	$0.35	$0.14	$0.35	$1.06			

Least Efficient Life-Cycle

	Energy Input	7 Bitumen Extraction	8 Refining and Distillation	9 Pipeline Transportation (Oklahoma to Wisc.)	10 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	948,000	863,628	824,966	643,473		643,473	0.64	4
Total BTUs Required	0	52,000	84,372	38,662	181,493	356,527			
Fossil BTUs Required	0	52,000	84,372	38,662	0	175,034			
Process Efficiency (%)	100%	94.80%	91.10%	95.52%	78.00%	64.35%			
Process Cost	0	$0.39	$1.10	$0.24	$2.26	$3.99			

Sources:

1,2,7,8

Extraction and refining Data - Argonne GREET 1.6 Model

Process cost Data - Department of Energy

* Crude oil price ($50.28)

* Electricity $0.0578 kW-hr

* N.G. wellhead price ($6.50 per 1000 cu.Ft.)

3,9

Pipeline Data - ANR pipeline Company

4,10

Furnace efficiency Data - Department of Energy

Process cost Data - Department of Energy ($12.79 per 1000 cu. Ft.)

Notes:

3,9

assume cost is 10% of tariff

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

11.0 Liquid Petroleum Gas

Liquid Petroleum gas (LPG) is very similar to natural gas. However, LPG consists mainly of propane and butane instead of methane. LPG is generally obtained from the refining and distillation of petroleum or natural gas. In 2005 alone, 316,468,000 gallons of LPG were delivered to Wisconsin (Wisconsin, 2006). Much of the LPG is used in home and commercial heating. Since 1987, LPG usage in Wisconsin has increased 39.6% (Wisconsin, 2006). The majority of LPG that is transported into Wisconsin enters via railcar or pipeline. LPG pipelines follow similar flow paths to that of natural gas and petroleum. However, LPG is compressed to a liquid before transportation. Wisconsin's main sources for LPG are Alberta Canada, Kansas, and the Gulf of Mexico[10].

LPG can be extracted from underground natural gas reservoirs, thus having the same extraction energy inputs as natural gas. Table 8 displays the efficiency of this process to be 97.2% with a cost of $0.22 per MMBTU. LPG can also be extracted during the process of petroleum extraction. In August of 2006, 2,490 thousand barrels of LPG were imported from Canada to the Midwest (U.S. DOE, 2006b). LPG extraction efficiency from bitumen oil sands in Canada is 94.8% with a cost of $0.39. Extraction efficiencies were taken from the Argonne GREET Model.

Refining costs and energy expenditures for LPG from bitumen oil sands is significantly higher than refinement from natural gas reservoirs. Table 8 displays that refining LPG from bitumen sands requires 61,620 BTUs per MMBTU while refining from natural gas extraction requires 34,020 BTUs per MMBTU. Refining efficiencies were taken from the GREET Model on natural gas and petroleum. Refining energy expenditures also account for the energy needed to condense LPG for transportation. The cost of refining from bitumen oil sands is nearly double the cost of refining from natural gas. The processing cost for refinement is based upon data provided by Marathon Oil Company.

---

[10] Information taken from personal interview with two LPG transporting companies

Most LPG is transported to Wisconsin via interstate pipelines or railcar. Before this is done, the LPG must be condensed to liquid petroleum (LP). Much of the LP transported to Wisconsin via pipeline comes from a large holding and finishing facility in Conway, Kansas. The distance LP must travel from Kansas to Wisconsin is 627 miles[11]. LP has an energy content of 21,300 BTU per pound (Energy Policy and Planning, 2006). With LP transport energy expenditures of 253 BTU per ton-mile (GREET Model), the total pipeline expenditure is 3,376 BTUs per MMBTU for the most efficient life-cycle. The tariff for LP transported from Conway, Kansas to Janesville, Wisconsin is $3.29 per barrel (Enterprise, 2006). Assuming a transportation cost of 10% of the tariff[12], the cost for transporting LP via pipeline is $0.08 per MMBTU. The cost of transportation via railcar is $0.05 if we assume an energy expenditure of 370 BTU per ton-mile for rail shipments of LP based upon GREET Model calculations. If an assumed travel distance of 1,400 miles is factored between Edmonton, Canada and Wisconsin; the energy requirements are 2,549 BTUs per MMBTU for rail which can be seen in Table 8.

Combustion efficiency represents the greatest cost in both life-cycles and results in over 75% of the total life-cycle cost in the least efficient cycle. Upper and lower combustion efficiencies were chosen to be 97% and 78% respectively (U.S. DOE, 2006). As seen in Table 8, a 78% efficient furnace results in combustion costs of $3.80 while combustion with a 98% efficient furnace is $0.54. Costs are figured assuming a residential LPG price of $1.76 per gallon for Wisconsin (U.S. DOE, 2006f). The net energy ratio is substantially reduced between life-cycles due in large part to the combustion efficiency difference. Fossil energy ratios and net energy output are decreased significantly with the least efficient life-cycle.

---

[11] Information taken from a personal interview with Jim Newer, a Controller for Enterprise Products Partners.

[12] Tariff information taken from a personal interview with Mitch Jones, Manager of Tariffs and Regulatory Affairs for BP.

Table 8 - LPG

Most Efficient Life-Cycle

	Energy Input	1 Extraction From Natural Gas	2 Refining from Natural Gas	3 Pipeline (Kansas to Wisconsin)	4 Combustion	Totals	Net Energy Output	5 Net Energy Ratio	6 Fossil Energy Ratio
Total BTU Remaining	1,000,000	972,000	937,980	934,604	906,584		906,584	0.91	14
Total BTUs Required	0	28,000	34,020	3,376	28,020	93,416			
Fossil BTUs Required	0	28,000	34,020	3,376	0	65,396			
Process Efficiency (%)	100%	97.20%	96.50%	99.64%	97.00%	90.66%			
Process Cost	0	$0.22	$0.44	$0.08	$0.54	$1.28			

Least Efficient Life-Cycle

	Energy Input	7 Extraction from Bitumen Oil Sands	8 Refining from Bitumen Oil Sands	9 Rail (Kansas to Wisconsin)	10 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	948,000	886,380	883,831	689,388		689,388	0.69	6
Total BTUs Required	0	52,000	61,620	2,549	194,442	310,611			
Fossil BTUs Required	0	52,000	61,620	2,549	0	116,169			
Process Efficiency (%)	100%	94.80%	93.50%	99.47%	78.00%	68.34%			
Process Cost	0	$0.39	$0.80	$0.05	$3.80	$5.04			

Sources:

1,2,7,8

Extraction, transportation, and refining energy Data - Argonne GREET 1.6 Model

Process cost Data - Department of Energy

* Crude oil price ($50.28)

* Electricity $0.0578 kW-hr

* N.G. wellhead price ($6.50 per 1000 cu.Ft.)

3,9

Energy and cost Data - Personal interview with Enterprise Products Partners

4,10

Furnace efficiency Data - Department of Energy

Fuel Cost Data - Department of Energy ($1.76 per gallon)

Notes:

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

9

Process cost Data - Department of Energy ($2.56 per gallon; diesel)

12.0 Conclusions

Examining the net energy ratio of wood fuel pellets demonstrates their overall competitiveness with other space heating fuel options. Table 9 shows that wood fuel pellets have an average net energy ratio of 0.73. This value falls just above the average net energy ratio of 0.72. Table 9 displays the net energy ratios of all eight heating fuels studied.

Table 9 – Net Energy Ratios

Fuel Type	**Most Efficient Net Energy Ratio**	**Least Efficient Net Energy Ratio**	**Average Net Energy Ratio**
Green Wood Chips	0.69	0.50	0.60
Corn	0.69	0.58	0.64
Geothermal	0.77	0.64	0.71
Wood Pellets	0.79	0.66	0.73
Heating Oil	0.82	0.65	0.74
Switchgrass	0.78	0.72	0.75
Natural Gas	0.89	0.64	0.77
LPG	0.91	0.69	0.80
AVERAGES	**0.79**	**0.64**	**0.72**

Examining life-cycle process expenditures is a beneficial way of displaying the competitive efficiency of heating fuels. Wood fuel pellets prove to be one of the most cost competitive heating fuels available via life-cycle assessment. Table 10 shows wood fuel pellets average life-cycle cost to be $2.98, the third most cost effective heating fuel behind green wood chips and natural gas.

Table 10 – Life Cycle Process Cost

Fuel Type	**Most Efficient Life-Cycle Cost**	**Least Efficient Life-Cycle Cost**	**Average Life-Cycle Cost**
Green Wood Chips	$1.64	$2.50	$2.07
Natural Gas	$1.06	$3.99	$2.53
Wood Pellets	$2.62	$3.33	$2.98
LPG	$1.28	$5.04	$3.16
Heating Oil	$2.33	$4.74	$3.54
Switchgrass	$3.26	$4.04	$3.65
Corn	$2.44	$5.30	$3.87
Geothermal	$6.69	$11.24	$8.97
AVERAGES	**$2.67**	**$5.02**	**$3.85**

There are several ways in which wood pellets net energy ratio and process cost can be further improved. Table 1 shows that stove efficiency values have the most significant effect on the net energy ratio and process cost. The second greatest energy expenditure is from drying of the wood feedstock. In the most efficient case displayed in Table 1, this can be avoided by securing dry feedstock from sources such as saw mills and wood fabrication facilities. Plant operations account for one of the greatest energy expenditures and process cost of the wood fuel life-cycle. Improving mill efficiency, as well as shifting production to times of off-peak electrical demand, are options available to further reduce process energy expenditures as well as lower overall life-cycle cost. An underlying cost and energy expenditure that can be seen Table 1 is the transportation expense. For the most efficient and least efficient cycle, transportation costs account for 18% and 14% of the total process cost respectively. Securing a supply of feedstock close to mill operations is one of the most effective ways in reducing overhead cost and energy expended from fuel.

Fossil energy ratios are also a vital piece of information that helps determine a fuels sustainability and environmental footprint. A low fossil energy input combined with a high net energy output result in a high fossil energy ratio. For heating oil, natural gas, LPG, and geothermal the entire life-cycle relies on fossil fuel energy making it a less sustainable process. The highest average fossil energy ratio of 31.0 was obtained by green wood chips, while the lowest fossil energy ratio of 2.5 was found with geothermal. Table 11 shows that wood fuel pellets have a fossil energy ratio of 11.5, the second highest amongst all heating fuels used in Wisconsin.

Table 11 – Fossil Energy Ratio

Fuel Type	Most Efficient Fossil Energy Ratio	Least Efficient Fossil Energy Ratio	Average Fossil Energy Ratio
Geothermal	3	2	2.5
Heating Oil	6	4	5.0
Natural Gas	12	4	8.0
Switchgrass	9	8	8.5
LPG	14	6	10.0
Corn	13	7	10.0
Wood Pellets	14	9	11.5
Green Wood Chips	45	17	31.0
AVERAGES	**14**	**7**	**10.8**

Life-cycle analysis of heating fuels for use in Wisconsin demonstrates that wood fuel pellets are amongst the most economical option, while obtaining one of the highest fossil energy ratios. Timber used to make wood pellets and green wood chips can be found within Wisconsin making it much more cost effective. Concerning net energy ratio, handling and transporting wood pellets can be more labor intensive than other fuels, thus decreasing the net energy ratio and leaving it below other fuels such as LPG and natural gas that have minimal transporting energy expenditures. Despite this, it can be deduced that pellet fuel for space heating is an efficient, competitive, and environmentally sustainable choice home owners and businesses.

13.0 Additional Questions

There are several further questions that can be posed in conjunction with this study. First, examining and comparing consumer costs for each fuel as well as examining fuel price history, futures, as well as fuel consumption and availability would be other avenues to investigate. Studying life-cycle efficiency values based upon systems that meet both the heating and hot water loads could also be evaluated in relation to this study. This study specifically focuses on heating fuels used in Wisconsin. Future studies could focus their attention of several geographic regions and further life-cycle comparisons could be made based upon this data. Differences in transportation distance and fuel cost will result in observable differences between locations. Finally, a follow-up study to examine the environmental impact of each heating fuels' life-cycle would be beneficial. The sustainability and environmental impact of heating fuels has become a more salient public topic. As global warming and the possibility of capping green house gases creeps into the political spotlight, and foreign oil is becoming linked to issues of national security and the economy, displaying fuels with a low environmental impact and minimal reliance on fossil fuels will become a vital part of life-cycle assessment.

Figure 1 – Process Cost and Fossil Energy Ratio Comparison

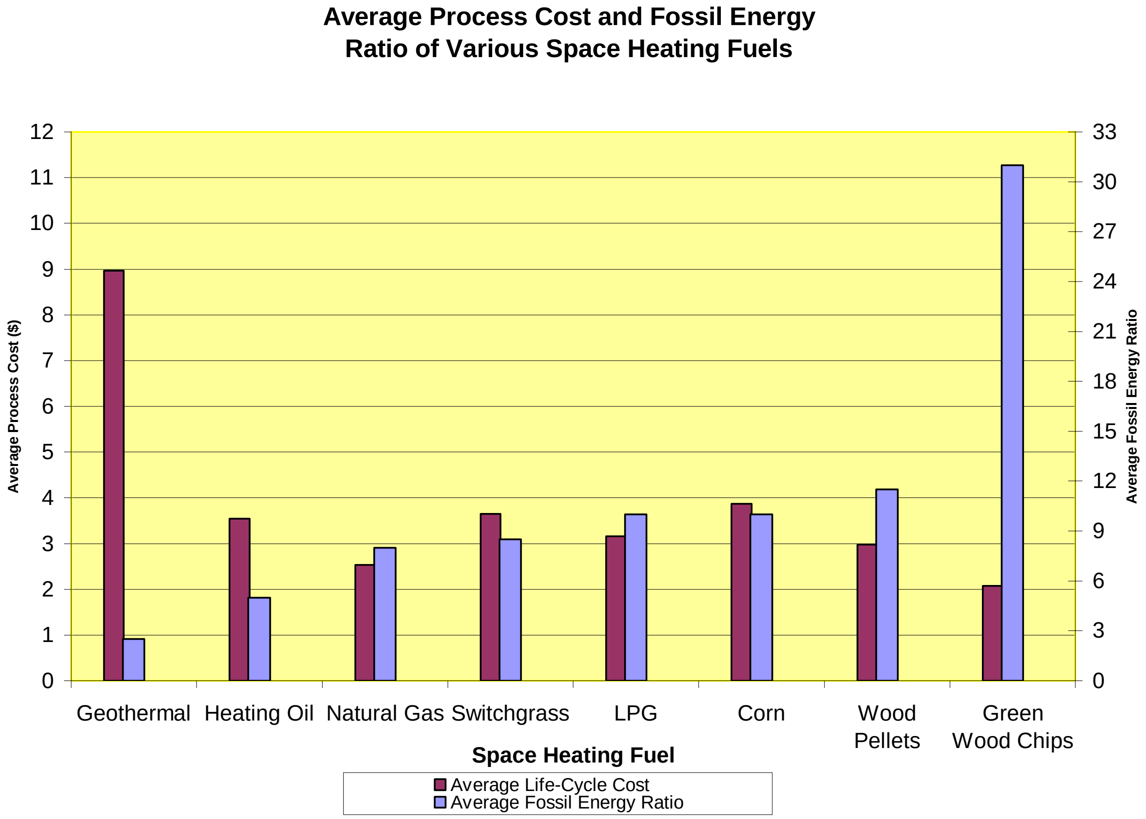
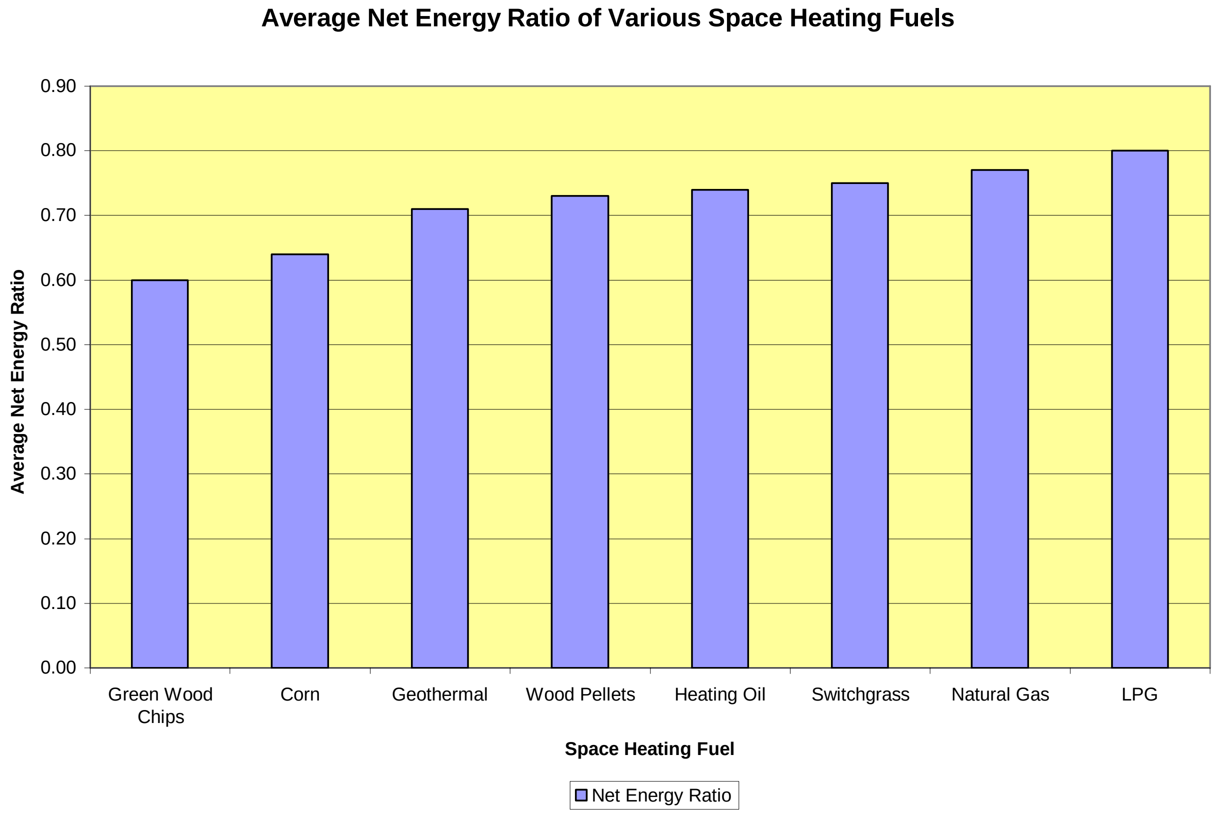


Figure 2 – Net Energy Ratio Comparison



REFERENCES

ANR Pipeline Company. (2006, April). *FERC gas tariff*. Retrieved July 26, 2006, from http://anrebb.elpaso.com/ebbANR/ebbmain.asp?sPipelineCode=ANR

Argonne National Laboratory. (2005, April 8). *The greenhouse gases, regulated emissions, and energy use in transportation (GREET) Model 1.6*. Retrieved July 20, 2006, from http://www.transportation.anl.gov/software/GREET/

Balch, M., Ney, R., Schnoor, J., Sivan, O., Solow, J. (2005, March 29). Estimating the economic impact of substituting switchgrass for coal for electrical generation in iowa. *Center for Global and Regional Environmental Research: The University of Iowa*. Retrieved September 9, 2006, from http://biomass.ecria.com/

Bioenergy Feedstock Information Network. (n.d.). *Biomass Energy*. Retrieved on November 28, 2006, from http://bioenergy.ornl.gov/papers/misc/energy_conv.html

Bi, X., Mani, S., Sokhansanj, S., Turhollow. (2006). *Economics of producing fuel pellets from biomass*. American Society of Agricultural and Biological Engineers, *22(3),* 421-426.

California Energy Commission. (2006, October 9). *Petroleum industry profile*. Retrieved October 9, 2006, from http://www.energy.ca.gov/pier/iaw/industry/petro.html

Canadian Association of Petroleum Producers. (n.d.) *Producing oil and natural gas*. Retrieved November 6, 2006, from http://www.capp.ca/

Chariton Valley RC&D. (n.d.).B*iomass project: home grown energy*. Retrieved October 23, 2006, from, http://biomass.ecria.com/index.html

Comnick, J., Johnson, L., Lippke, B., Marshall, J. (2005). Life-cycle impacts of forest resource activities in the pacific northwest and southeast united states. *Wood and Fiber Science, 12,* 30—46.

Daly, M., Graham, R., Noon, C., Zahn, F. (1996). *Transportation and site location analysis for regional integrated biomass assessment*. Retrieved September 4, 2006, from http://bioenergy.ornl.gov/papers/bioen96/noon1.html

Drisdelle, M., Duxbury. P., Lapointe, C., Mulkins, L., Samson, R. (2000). *The use of switchgrass biofuel pellets as a greenhouse gas offset strategy.* Retrieved September 12, 2006, from http://www.reapcanada.com/online_library/Reports%20and%20Newsletters/Bioenergy/2%20The%20Use.ppt.

Duffield, J., Graboski, M., Shapouri, H. (1995, July). Estimating the net energy balance of corn ethanol: An economic research service report. *United States Department of Agriculture, Agricultural Economic Report Number 721*. Retrieved September 14, 2006, from http://www.ethanol-gec.org/

Duxbury, P., Samson, R. (2000, April). *Assessment of pelletized biofuels*. Retrieved October 23, 2006, from http://www.reap-canada.com/library.htm

Enbridge Energy, Limited Partnership. (2006, May 31). *Local tariff applying on crude petroleum and natural gas liquid*. Retrieved July 10, 2006, from http://www.enbridge.com/

Energy Policy and Planning Office. (2006). *Oil industry conversions*. Retrieved August 20,2006, from http://www.eppo.go.th/ref/UNIT-OIL.html

Enterprise Products Partners L.P. (2006, March). *MAPL/ seminole tariffs*. Retrieved November 6, 2006, from http://tariffs.eprod.com/directory/MAPLLC_NGL/FERC/ Current/ MAPLLLC_FERC_No-41.pdf

Girouard, P., Medhi, B., Samson, R., Zan, C. (1999, July). *Economics and carbon offset potential of biomass fuels.* Resource Efficient Agriculture Production (R.E.A.P.) Canada. Retrieved October 4, 2006, from http://www.reap-canada.com/online_library/ Reports%20and%20Newsletters/Bioenergy/17%20Economics%20and.pdf

Maier, D., Uhrig, J.(1992, October 1). Cost of drying high-moisture corn. *Purdue University Grain Quality Task Force, Grain Quality Fact Sheet #3.* Retrieved August 22, 2006, from http://www.ces.purdue.edu/

Maker, T. (2004). Wood-Chip Heating Systems: A guide for institutional and commercial biomass installation. *Biomass Energy Resource Center.* Retrieved November 25, 2006, from, www.biomasscenter.org/pdfs/wood-chip-heating-guide.pdf

National Corn Growers Association. (2006, November). *DJ CBOT corn outlook.* Retrieved on November 29, 2006, from http://ncga.ncgapremium.com/ index.aspx?ascxID=dowJones&category=1&djid=15277

Pellet Fuel Institute. (n.d.). *Comparing Fuel Costs*. Retrieved on October 3, 2006, from http://www.pelletheat.org

Penn State University. (2003, July). *Heat energy content of shelled corn*. Retrieved on November 6, 2006, from http://energy.cas.psu.edu/energycontent.html

Penn State University. (2002). *Burning shelled corn to produce heat energy.* Retrieved on November 26, 2006, from http://www.energy.iastate.edu/renewable/biomass/ download/corn_burner.pdf

Puettman, M., Wilson, J. (2005). Life-Cycle Analysis of Wood Products: Cradle-to-gate LCI of residential wood building materials. *Wood and Fiber Science, 37*, 18—29.

Quan, Y., Samson, R., Jannasch, R., (2001). A process and energy analysis of pelletizing switchgrass. *Natural Resource Canada, Alternative Energy Division*. Retrieved September 14, 2006, from http://www.reap-canada.com/library.htm

Spieser, H. (1993, August). *Burning shelled corn as a heating fuel*. Retrieved September 13, 2006, from http://www.omafra.gov.on.ca/english/engineer/facts/93-023.htm

U.S. Department of Agriculture (2002). *2002 Census of Agriculture State Profile.* Retrieved October 25, 2006 from http://www.nass.usda.gov/census/census02/profiles/wi/index.htm

U.S. Department of Agriculture: Forest Products Laboratory. (2004, July). *Fuel value calculator*. Retrieved September 22, 2006, from http://www.fpl.fs.fed.us/

U.S. Department of Agriculture: Risk Management Agency. (2005, December). *2005 Commodity insurance fact sheet*. Retrieved September 14, 2006, from http://www.usda.gov/

U.S. Department of Energy: Energy Efficiency and Renewable Energy. (2006, February 14). *Energy efficient products*. Retrieved August 15, 2006, from http://www.eere.energy.gov/femp/procurement/eep_gas_furnace.cfm

U.S. Department of Energy: Energy Efficiency and Renewable Energy. (2005a, September). *Wood and pellet heat.* Retrieved October 14, 2006, from http://www.eere.energy.gov/consumer/ your_home/space_heating_cooling/index.cfm/mytopic=12570

U.S. Department of Energy: Energy Efficiency and Renewable Energy. (2005b, September). *Selecting and Installing a Geothermal Heat Pump System*. Retrieved October 2, 2006, from http://www.eere.energy.gov/

U.S. Department of Energy: Energy Efficiency and Renewable Energy. (2005c, August). *Wood/wood waste.* Retrieved November 25, 2006, from http://www.eia.doe.gov/cneaf/solar.renewables/ page/wood/wood.html

U.S. Department of Energy: Energy Information Administration. (2006a, October). *Crude oil prices*. Retrieved August 12, 2006, from http://www.eia.doe.gov/oil_gas/petroleum/ info_glance/crudeoil.html

U.S. Department of Energy: Energy Information Administration. (2006b, October). *Heating oil and propane update*. Retrieved November 6, 2006, from http://www.eia.doe.gov/oog/info/hopu/ hopu.asp

U.S. Department of Energy: Energy Information Administration. (2006c, September 26). *Natural gas prices*. Retrieved September 28, 2006, from http://www.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm

U.S. Department of Energy: Energy Information Administration. (2006d, August 28). *Retail on highway diesel prices*. Retrieved November 10, 2006 from http://tonto.eia.doe.gov/oog/info/wohdp/diesel_detail_report.asp

U.S. Department of Energy: Energy Information Administration. (2006e, May). *Electric power monthly*. Retrieved July 28, 2006, from http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html

U.S. Department of Energy: Energy Information Administration. (2006f, March 15). *Weekly heating oil and propane prices*. Retrieved July 12, 2006, from http://tonto.eia.doe.gov/dnav/pet/ pet_pri_wfr_dcus_nus_w.htm

U.S. Department of Energy: Energy Information Administration. (2006g, January). *Natural gas processing: the crucial link between natural gas production and its transportation to market.* Retrieved October 10, 2006, from http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngprocess/ngprocess.pdf

U.S. Department of Energy: Energy Information Administration. (2005, November 25). *Heating fuel comparison calculator*. Retrieved July 10, 2006, from http://www.eia.doe.gov/neic/experts/ heatcalc.xls

U.S. Department of Energy: Energy Information Administration. (2004). *Survey of geothermal heat pump shipments.* Retrieved on October 27, 2006, from http://www.eia.doe.gov/cneaf/ solar.renewables/page/heatpumps/heatpumps.html

U.S. Environmental Protection Agency: Energy Star. (2007). *Furnaces.* Retrieved on January 26, 2007 from http://www.energystar.gov/

Wisconsin Ag Connection. (2006, November). *Grain prices up, cattle prices down in october*. Retrieved November 17, 2006, from http://www.wisconsinagconnection.com/

Wisconsin Department of Administration. (2006). *Wisconsin energy statistics*. Retrieved October 27, 2006, from http://www.doa.state.wi.us/

Wisconsin Department of Natural Resources. (2004). *Wisconsin's Statewide Forest Plan: Ensuring a sustainable future*. Retrieved November 11, 2006, from http://dnr.wi.gov/org/land/ forestry/fia/highlights2004.htm

Appendix

Table 1 - Wood Pellets

Most Efficient Life-Cycle

	Energy Input	1 Transporting Feedstock to Plant	2 Plant Operations	3 Transporting final Product	4 Water Vaporization at 8% Moisture	5 Combustion	Totals	Net Energy Output	6 **Net Energy Ratio**	7 **Fossil Energy Ratio**
Total BTU Remaining	1,000,000	987,249	957,488	943,755	924,219	785,586		785,586	0.79	14
Total BTUs Required	0	12,751	29,760	13,733	19,535	138,632	214,411			
Fossil BTUs Required	0	12,751	29,760	13,733	0	0	56,244			
Process Efficiency (%)	100%	98.72%	96.99%	98.57%	97.93%	85.00%	78.56%			
Process Cost	0	$0.24	$0.51	$0.26	$0.20	$1.41	$2.66			

Least Efficient Life-Cycle

	Energy Input	Harvesting and Loading	8 Chipping Feedstock	Transporting Feedstock to Plant	9 Drying (55% to 12%)	Plant Operations	Transporting Final Product	Water Vaporization at 8% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	981,496	978,933	966,403	905,811	878,546	866,279	848,350	661,713		661,713	0.66	9
Total BTUs Required	0	18,504	2,563	12,530	60,592	27,265	12,567	17,929	186,637	338,587			
Fossil BTUs Required	0	18,504	2,563	12,530	0	27,265	12,567	0	0	73,429			
Process Efficiency (%)	100%	98.15%	99.74%	98.72%	93.73%	96.99%	98.57%	97.93%	78.00%	66.15%			
Process Cost	0	$0.15	$0.05	$0.24	$0.11	$0.46	$0.23	$0.18	$1.91	$3.33			

Sources:

1

Transportation energy Data - Department of Energy

Transportation Data - Personal interviews with 5 pellet fuel companies

2

Operations Data - from interviews with 2 pellet fuel companies

Process cost Data - Department of Energy ($.0578 per kW-hr)

3

Shipping Data - from interviews with 5 pellet fuel companies

Transportation energy Data - Department of Energy

5

Fuel cost Data - $165 per ton (Pellet Fuel Institute)

Combustion efficiency Data - Dept. of Energy

Notes:

4

Assume an energy expenditure of 1115 Btu per lb. water

6

Net energy ratio = net energy output/ energy input

7

Fossil energy ratio =net energy output/ fossil energy used

8

Assume 500 HP Hammer Mill at 50 tons per hour output

9

Assume $20 per ton cost of feedstock

Assume product is dried from companies own feedstock

Table 2 - Green Wood Chips

Most Efficient Life-Cycle

	1 Energy Input	2 Clear Cut Felling	3 Clear Cut Yarding	4 Loading	5 Chipping Feedstock	6 Rail Transport	7 Water Vaporization at 55% Moisture	8 Combustion	Totals	Net Energy Output	9 Net Energy Ratio	10 Fossil Energy Ratio
Total BTU Remaining	1,000,000	999,660	994,593	992,136	989,546	984,824	914,579	685,934		685,934	0.69	45
Total BTUs Required	0	340	5,067	2,457	2,590	4,722	70,245	228,645	314,066			
Fossil BTUs Required	0	340	5,067	2,457	2,590	4,722	0	0	15,176			
Process Efficiency (%)	100%	99.97%	99.49%	99.75%	99.74%	99.52%	92.87%	75.00%	68.59%			
Process Cost	0	$0.01	$0.09	$0.05	$0.05	$0.09	$0.32	$1.03	$1.64			

Least Efficient Life-Cycle

	Energy Input	11 Site Preparation, Planting, Growing, Harvesting	12 Loading	Chipping Feedstock	Rail Transport	13 On-road Transport	Water Vaporization at 55% Moisture	14 Combustion	Totals	Net Energy Output	Net Energy Ratio	Fossil Energy Ratio
Total BTU Remaining	1,000,000	988,542	981,625	979,063	974,391	971,357	902,091	496,150		496,150	0.50	17
Total BTUs Required	0	11,458	6,917	2,563	4,672	3,034	69,266	405,941	503,851			
Fossil BTUs Required	0	11,458	6,917	2,563	4,672	3,034	0	0	28,644			
Process Efficiency (%)	100%	98.85%	99.30%	99.74%	99.52%	99.69%	92.87%	55.00%	49.61%			
Process Cost	0	$0.02	$0.13	$0.05	$0.09	$0.06	$0.32	$1.83	$2.50			

Sources:

1,2,3,4,6,11,12

Harvest Data - From two studies by Wood and Fiber Science Magazine, Corrim Special Issue

8,14

Combustion efficiency Data - Biomass Energy Resource Center

Notes:

5

Assume 500 HP Hammer Mill at 50 tons per hour

7

Assume an energy expenditure of 1115 Btu per lb. water

9

Net energy ratio = net energy output/ energy input

10

Fossil energy ratio =net energy output/ fossil energy used

13

Assume 25 mile travel distance

Process cost Data - Department of Energy ($2.56 gallon; diesel)

Table 3 - Corn

Most Efficient Life-Cycle

		1	2	3	4			5	6
	Energy Input	Corn Establishment, Fertilization, and Harvest	Drying With Natural Gas (22% to 15%)	Water Vaporization at 15% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	976,788	945,290	922,745	692,059		692,059	0.69	13
Total BTUs Required	0	23,212	31,498	22,545	230,686	307,941			
Fossil BTUs Required	0	23,212	31,498	0	0	54,710			
Process Efficiency (%)	100%	97.68%	96.78%	97.62%	75.00%	69.21%			
Process Cost	0	$0.43	$0.39	$0.14	$1.48	$2.44			

Least Efficient Life-Cycle

			7		8				
	Energy Input	Corn Establishment, Fertilization, and Harvest	Drying With Electricity (30% to 15%)	Water Vaporization at 15% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	975,833	916,090	894,236	581,253		581,253	0.58	7
Total BTUs Required	0	24,167	59,743	21,854	312,983	418,747			
Fossil BTUs Required	0	24,167	59,743	0	0	83,910			
Process Efficiency (%)	100%	97.58%	93.88%	97.61%	65.00%	58.12%			
Process Cost	0	$0.45	$1.75	$0.20	$2.90	$5.30			

Sources:

1

Planting and harvesting Data - Department of Agriculture

2

Drying Data - Agricultural harvest study, Purdue University

Process cost Data - Department of Energy ($12.79 per 1000 cu. Ft.)

4

Combustion Data - Penn State University

Fuel cost Data - Wisconsin Ag Connection ($2.50 bushel)

7

Process cost Data - Department of Energy ($.0999 kW-hr.)

8

Fuel cost Data - National Corn Growers Association ($3.61)

Notes:

3

Assume an energy expenditure of 1115 Btu per lb. water

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

Table 4 - Switchgrass

Most Efficient Life-Cycle

		1	2	3		4	5			6	7
	Energy Input	Switchgrass Establishment, Fertilization, Harvest	Transportation (5 miles)	Pellet Mill Operations	Transporting final Product	Water Vaporization at 9% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	949,681	949,016	926,999	913,743	899,763	782,793		782,793	0.78	9
Total BTUs Required	0	50,319	665	22,017	13,256	13,980	116,970	217,207			
Fossil BTUs Required	0	50,319	665	22,017	13,256	0	0	86,257			
Process Efficiency (%)	100%	94.97%	99.93%	97.68%	98.57%	98.47%	87.00%	78.28%			
Process Cost	0	$0.93	$0.01	$0.37	$0.25	$0.18	$1.52	$3.26			

Least Efficient Life-Cycle

			8	9				10				
	Energy Input	Switchgrass Establishment, Fertilization, Harvest	Transportation (50 miles)	Drying (20% moisture to 14.5%)	Pellet Mill Operations	Transporting final Product	Water Vaporization at 9% Moisture	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	949,681	942,653	930,909	909,777	896,767	883,047	715,268		715,268	0.72	8
Total BTUs Required	0	50,319	7,027	11,744	21,131	13,009	13,720	167,779	284,729			
Fossil BTUs Required	0	50,319	7,027	0	21,131	13,009	0	0	91,486			
Process Efficiency (%)	100%	95.41%	99.26%	98.76%	97.73%	98.57%	89.73%	81.00%	65.49%			
Process Cost	0	$0.85	$0.11	$0.04	$0.37	$0.24	$0.18	$2.17	$3.96			

Sources:

1

Switchgrass Data - R.E.A.P. - Canada

Process cost Data - Department of Energy ($2.56 gallon; diesel)

3

Pellet mill Data - taken from 2 studies completed by R.E.A.P. - Canada

Process cost Data - Department of Energy ($.0578 per kW-hr)

5,10

Fuel cost Data - Forest Products Laboratory ($186 per dry ton)

Efficiency Data - R.E.A.P. Canada

Notes:

2,8

Assuming variable distance from harvest region

5,9

Assume an energy expenditure of 1115 Btu per lb. water

6

Net energy ratio = net energy output/ energy input

7

Fossil energy ratio =net energy output/ fossil energy used

9

Feedstock price - assume $50 per ton

Table 5 - Geothermal

Most Efficient Life-Cycle

	Energy Input	1 Compressor, Fan, External, Internal Pump	Totals	Net Energy Output	3 **Net Energy Ratio**	4 **Fossil Energy Ratio**
Total BTU Remaining	1,000,000	769,054		769,054	0.77	3
Total BTUs Required	0	230,946	230,946			
Fossil BTUs Required	0	230,946	230,946			
Process Efficiency (%)	100%	71.65%	71.65%			
Process Cost	0	$6.69	$6.69			

Least Efficient Life-Cycle

	Energy Input	5 Compressor, Fan, External, Internal Pump	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	642,857		642,857	0.64	2
Total BTUs Required	0	357,143	357,143			
Fossil BTUs Required	0	357,143	357,143			
Process Efficiency (%)	100%	64.29%	64.29%			
Process Cost	0	$11.24	$11.24			

Sources:

1

Compressor, fan, pump data - Specification catalogs of 3 geothermal manufacturers

5

Compressor, fan, pump Data - Department of Energy

Process cost Data - Department of Energy ($0.0999 kW-hr)

Notes:

3

Net energy ratio = net energy output/ energy input

4

Fossil energy ratio =net energy output/ fossil energy used

5

Assume a 2.8 coefficiency of performance

Table 6 - Heating Oil

Most Efficient Life-Cycle

	Energy Input	1 Extraction from Oil Reservoir	2 Refining	3 Pipe Transport	4 Jobber Transport	5 Retail Transport	6 Combustion	Totals	Net Energy Output	7 **Net Energy Ratio**	8 **Fossil Energy Ratio**
Total BTU Remaining	1,000,000	980,000	877,100	875,544	874,231	866,190	822,881		822,881	0.82	6
Total BTUs Required	0	20,000	102,900	1,556	1,313	8,041	43,310	177,120			
Fossil BTUs Required	0	20,000	102,900	1,556	1,313	8,041	0	133,810			
Process Efficiency (%)	100%	98.00%	89.50%	99.82%	99.85%	99.08%	95.00%	82.29%			
Process Cost	0	$0.13	$1.32	$0.03	$0.03	$0.14	$0.68	$2.33			

Least Efficient Life-Cycle

	Energy Input	9 Extraction from Bitumen Sands	Refining	Pipe Transport	Jobber Transport	Retail transport	10 Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	948,000	848,460	846,956	845,686	837,906	653,766		653,766	0.65	4
Total BTUs Required	0	52,000	99,540	1,504	1,270	7,780	184,140	346,234			
Fossil BTUs Required	0	52,000	99,540	1,504	1,270	7,780	0	162,094			
Process Efficiency (%)	100%	94.80%	89.50%	99.82%	99.85%	99.08%	78.00%	65.38%			
Process Cost	0	$0.39	$1.28	$0.03	$0.03	$0.14	$2.87	$4.74			

Sources:

1,9

Energy Data - Argonne GREET 1.6 Model

Process cost Data - California Energy Commission

2

Process energy and cost Data - Personal Interview with Murphy Oil Refinery

3

Transport energy Data - Embridge Energy Limited Partnership

Transport energy Cost - Personal interview with BP tariff regulatory manager

4,5

Energy Data - Personal interviews with fuel transporters in Wisconsin

6,10

Furnace efficiency Data - Department of Energy
- US EPA (Energy Star)

Notes:

7

Net energy ratio = net energy output/ energy input

8

Fossil energy ratio =net energy output/ fossil energy used

Table 7 - Natural Gas

Most Efficient Life-Cycle

		1	2	3	4			5	6
	Energy Input	Extraction from NG Reserve	Refining and Distillation	Pipeline Transportation (gulf to Wisc.)	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	972,000	944,784	922,582	894,905		894,905	0.89	12
Total BTUs Required	0	28,000	27,216	22,202	27,678	105,096			
Fossil BTUs Required	0	28,000	27,216	22,202	0	77,418			
Process Efficiency (%)	100%	97.20%	97.20%	97.65%	97.00%	89.49%			
Process Cost	0	$0.22	$0.35	$0.14	$0.35	$1.06			

Least Efficient Life-Cycle

		7	8	9	10				
	Energy Input	Bitumen Extraction	Refining and Distillation	Pipeline Transportation (Oklahoma to Wisc.)	Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	948,000	863,628	824,966	643,473		643,473	0.64	4
Total BTUs Required	0	52,000	84,372	38,662	181,493	356,527			
Fossil BTUs Required	0	52,000	84,372	38,662	0	175,034			
Process Efficiency (%)	100%	94.80%	91.10%	95.52%	78.00%	64.35%			
Process Cost	0	$0.39	$1.10	$0.24	$2.26	$3.99			

Sources:

1,2,7,8

Extraction and refining Data - Argonne GREET 1.6 Model

Process cost Data - Department of Energy

* Crude oil price ($50.28)

* Electricity $.0578 kW-hr

* N.G. wellhead price ($6.50 per 1000 cu.Ft.)

3,9

Pipeline Data - ANR pipeline Company

4,10

Furnace efficiency Data - Department of Energy

Process cost Data - Department of Energy ($12.79 per 1000 cu. Ft.)

Notes:

3,9

assume cost is 10% of tariff

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

Table 8 - LPG

Most Efficient Life-Cycle

	Energy Input	1 Extraction From Natural Gas	2 Refining from Natural Gas	3 Pipeline (Kansas to Wisconsin)	4 Combustion	Totals	Net Energy Output	5 **Net Energy Ratio**	6 **Fossil Energy Ratio**
Total BTU Remaining	1,000,000	972,000	937,980	934,604	906,584		906,584	0.91	14
Total BTUs Required	0	28,000	34,020	3,376	28,020	93,416			
Fossil BTUs Required	0	28,000	34,020	3,376	0	65,396			
Process Efficiency (%)	100%	97.20%	96.50%	99.64%	97.00%	90.66%			
Process Cost	0	$0.22	$0.44	$0.08	$0.54	$1.28			

Least Efficient Life-Cycle

	Energy Input	7 Extraction from Bitumen Oil Sands	8 Refining from Bitumen Oil Sands	9 Rail (Kansas to Wisconsin)	10 Combustion	Totals	Net Energy Output	**Net Energy Ratio**	**Fossil Energy Ratio**
Total BTU Remaining	1,000,000	948,000	886,380	883,831	689,388		689,388	0.69	6
Total BTUs Required	0	52,000	61,620	2,549	194,442	310,611			
Fossil BTUs Required	0	52,000	61,620	2,549	0	116,169			
Process Efficiency (%)	100%	94.80%	93.50%	99.47%	78.00%	68.34%			
Process Cost	0	$0.39	$0.80	$0.05	$3.80	$5.04			

Sources:

1,2,7,8

Extraction, transportation, and refining energy Data - Argonne GREET 1.6 Model

Process cost Data - Department of Energy

* Crude oil price ($50.28)

* Electricity $.0578 kW-hr

* N.G. wellhead price ($6.50 per 1000 cu.Ft.)

3,9

Energy and cost Data - Personal interview with Enterprise Products Partners

4,10

Furnace efficiency Data - Department of Energy

Fuel Cost Data - Department of Energy ($1.76 per gallon)

Notes:

5

Net energy ratio = net energy output/ energy input

6

Fossil energy ratio =net energy output/ fossil energy used

9

Process cost Data - Department of Energy ($2.56 per gallon; diesel)

Table 9 – Net Energy Ratios

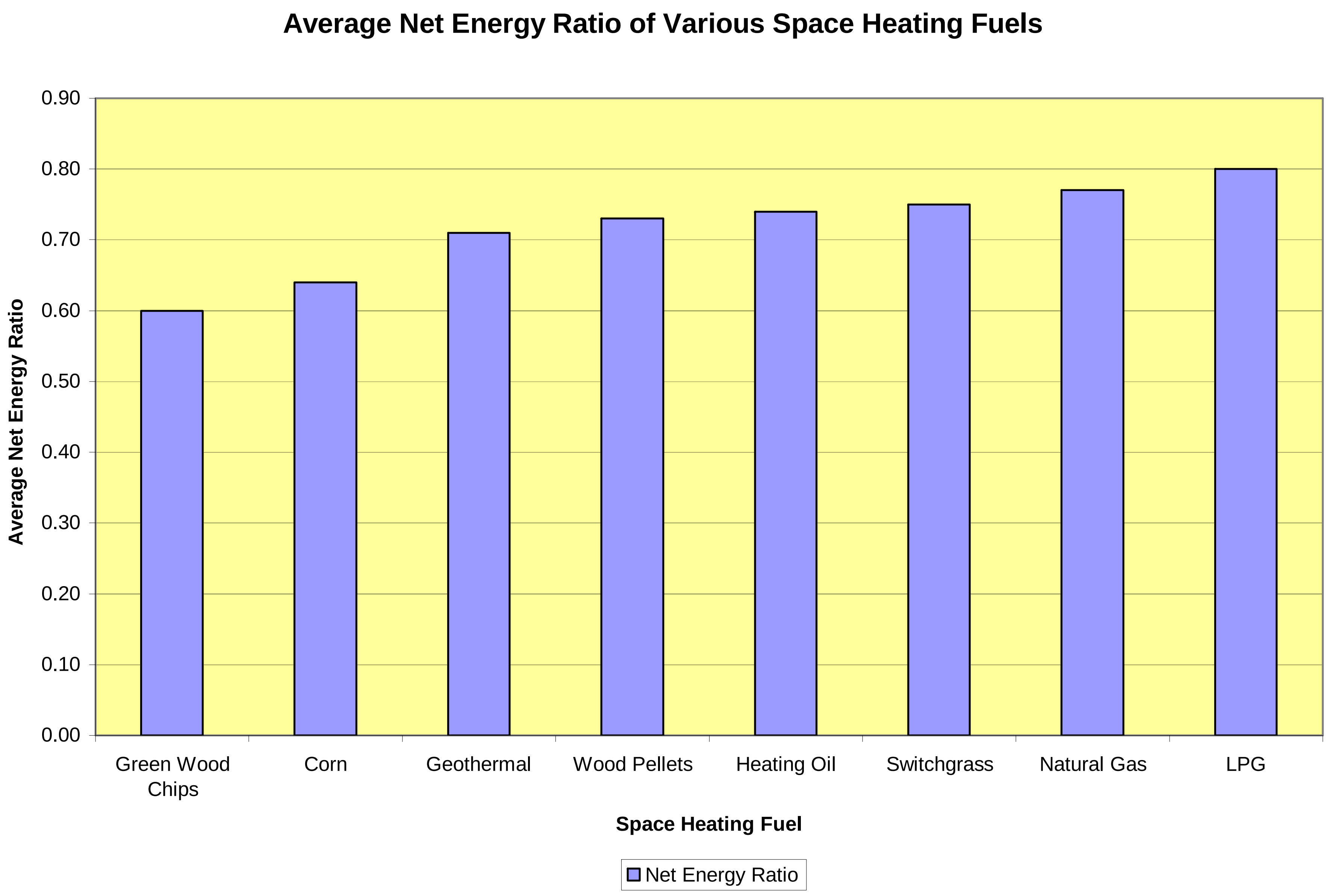
Fuel Type	**Most Efficient Net Energy Ratio**	**Least Efficient Net Energy Ratio**	**Average Net Energy Ratio**
Green Wood Chips	0.69	0.50	0.60
Corn	0.69	0.58	0.64
Geothermal	0.77	0.64	0.71
Wood Pellets	0.79	0.66	0.73
Heating Oil	0.82	0.65	0.74
Switchgrass	0.78	0.72	0.75
Natural Gas	0.89	0.64	0.77
LPG	0.91	0.69	0.80
AVERAGES	**0.79**	**0.64**	**0.72**

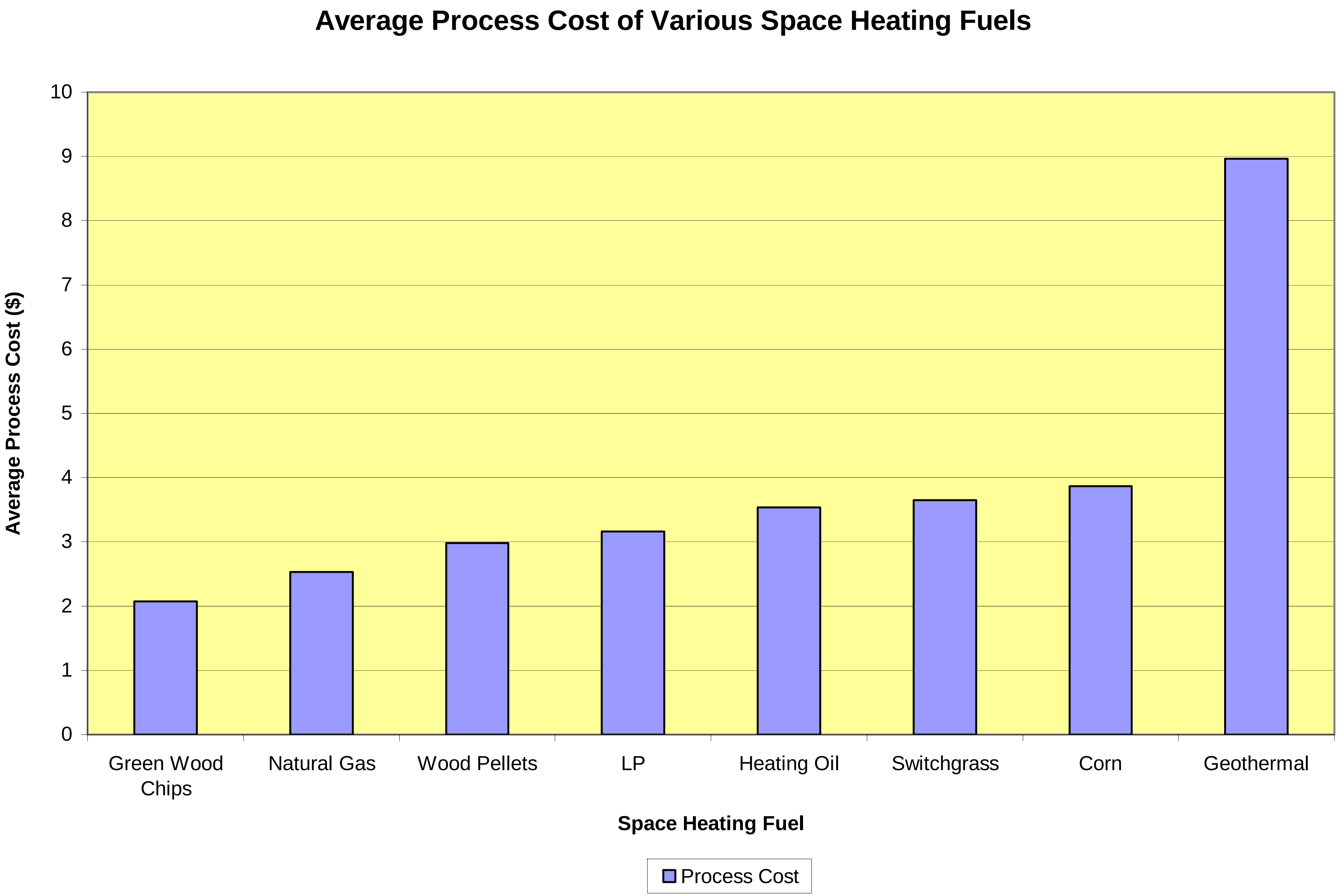
Table 10 – Life Cycle Process Cost

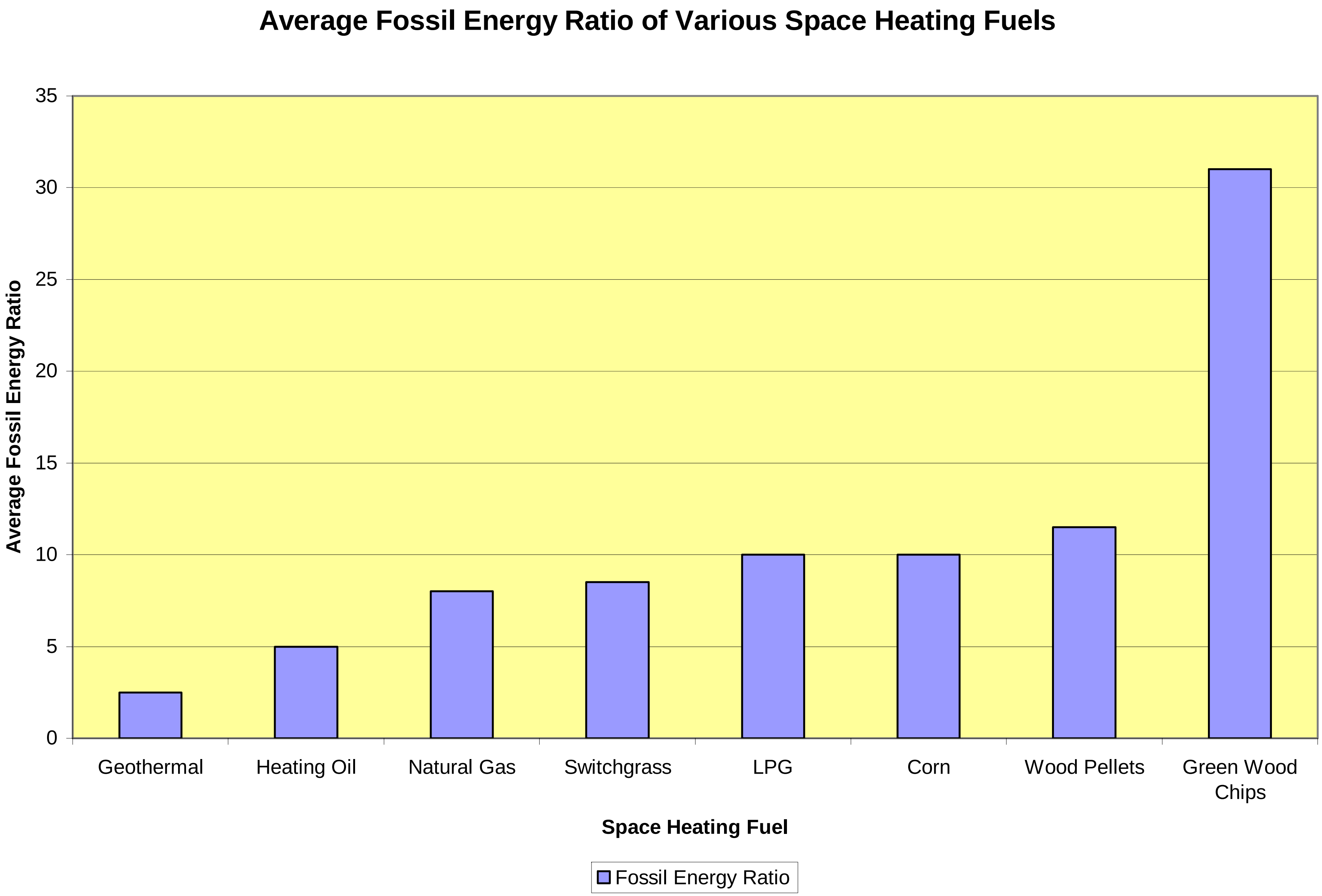
Fuel Type	**Most Efficient Life-Cycle Cost**	**Least Efficient Life-Cycle Cost**	**Average Life-Cycle Cost**
Green Wood Chips	$1.64	$2.50	$2.07
Natural Gas	$1.06	$3.99	$2.53
Wood Pellets	$2.62	$3.33	$2.98
LP	$1.28	$5.04	$3.16
Heating Oil	$2.33	$4.74	$3.54
Switchgrass	$3.26	$4.04	$3.65
Corn	$2.44	$5.30	$3.87
Geothermal	$6.69	$11.24	$8.97
AVERAGES	**$2.67**	**$5.02**	**$3.85**

Table 11 – Fossil Energy Ratio

Fuel Type	**Most Efficient Fossil Energy Ratio**	**Least Efficient Fossil Energy Ratio**	**Average Fossil Energy Ratio**
Geothermal	3	2	2.5
Heating Oil	6	4	5.0
Natural Gas	12	4	8.0
Switchgrass	9	8	8.5
LPG	14	6	10.0
Corn	13	7	10.0
Wood Pellets	14	9	11.5
Green Wood Chips	45	17	31.0
AVERAGES	**14**	**7**	**10.8**


Average Net Energy Ratio of Various Space Heating Fuels
Average Net Energy Ratio
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Green Wood Chips
Corn
Geothermal
Wood Pellets
Heating Oil
Switchgrass
Natural Gas
LPG
Space Heating Fuel
Net Energy Ratio


Average Process Cost of Various Space Heating Fuels
Average Process Cost ($)
10
9
8
7
6
5
4
3
2
1
0
Green Wood Chips
Natural Gas
Wood Pellets
LP
Heating Oil
Switchgrass
Corn
Geothermal
Space Heating Fuel
Process Cost


Average Fossil Energy Ratio of Various Space Heating Fuels
Average Fossil Energy Ratio
35
30
25
20
15
10
5
0
Geothermal
Heating Oil
Natural Gas
Switchgrass
LPG
Corn
Wood Pellets
Green Wood Chips
Space Heating Fuel
Fossil Energy Ratio