Prospects for Increased Low-Grade Bio-fuels Use in Home and Commercial Heating Applications

by

John Robert Pendray

Bachelor of Science in Mechanical Engineering,
North Dakota State University, 1999

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy

at the

Massachusetts Institute of Technology

June 2007

©2007 Massachusetts Institute of Technology.
All rights reserved.

Signature of Author……………………………………………………………………………………………
Technology and Policy Program, Engineering Systems Division
May 7, 2007

Certified by……………………………………………………………………………………………………
Ernest J. Moniz, PhD
Cecil and Ida Green Professor of Physics and Engineering Systems
Co-Director Laboratory for Energy and the Environment
Thesis Supervisor

Certified by……………………………………………………………………………………………………
Daniel Cohn, PhD
Senior Research Scientist, Laboratory for Energy and the Environment
Thesis Supervisor

Accepted by……………………………………………………………………………………………………
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

Prospects for Increased Low-Grade Bio-fuels Use in Home and Commercial Heating Applications

by

John Robert Pendray

Submitted to the Engineering Systems Division
on May 7, 2007 in Partial Fulfillment of the Requirement for the
Degree of Master of Science in Technology and Policy

Abstract

Though we must eventually find viable alternatives for fossil fuels in large segments of the energy market, there are economically attractive fossil fuel alternatives today for niche markets. The easiest fossil fuels to replace are those with the highest cost and that provide the lowest-grade energy. Stationary heating with oil is one example of low quality use of a high quality fuel.

Solid biomass fuels such as wood-pellets, switchgrass-pellets, and corn can displace up to 2% of the U.S. petroleum market through displacing oil used in home and commercial heating. Current technologies are inexpensive enough to enable consumers to save money by heating with solid bio-fuels instead of oil. Although these systems are currently difficult to operate, future systems can increase usability and potentially further reduce costs. Key developments for future adoption are fuel handling and ash cleaning automation as well as emissions reductions. These technologies exist in other industries, such as agriculture, but have not yet been integrated into U.S. solid bio-fuel heating systems.

Solid bio-fuel heating is more effective at reducing environmental damage and increasing energy security than corn-ethanol. Net CO_2 emissions from solid bio-fuel heating are 75% lower than oil heating, in contrast to the nearly equivalent CO_2 emissions between corn-ethanol and gasoline. The total solid bio-fuel system evaluated included fuel feedstock cultivation, harvesting, processing, and processed fuel distribution. Solid bio-fuel heating also enables cellulosic feedstocks use today. Solid bio-fuel heating also displaces twice the oil of corn-ethanol for the same amount of corn consumed, displacing 7 to 11 times the petroleum consumed during solid bio-fuel production and distribution. Solid bio-fuels are also less likely to negatively impact the food supply, because heating oil demand matches biomass fuel supply more closely than transportation fuel demand. This decreases the likelihood of price shocks in the food supply. This paper does not advocate using food for fuel, but does show that burning corn for heat is a more energy and cost effective use for the limited food supply than corn-ethanol.

Low grade biomass fuels provide the ecological benefits of alternative fuels while economically benefiting consumers. Solid bio-fuel heating is economically competitive with heating oil, utilizes existing infrastructures and technologies, and provides measurable reductions in oil consumption and greenhouse gas emissions.

Thesis Supervisor: Ernest J. Moniz
Title: Cecil and Ida Green Professor of Physics and Engineering Systems
Co-Director Laboratory for Energy and the Environment

Thesis Supervisor: Daniel Cohn
Title: Senior Research Scientist, Laboratory for Energy and the Environment

Table of Contents

List of Figures

1 Introduction

Fossil fuel consumption creates pressure on the environment and international relations. Environmental strains such as global climate change, acid rain, and smog occur at the global, regional, and local levels, respectively. All fossil fuel consumption contributes to one or more of these environmental effects. International tensions arise from geographical and political separation between fossil fuel supply and demand. Petroleum trading currently creates most of that tension, though increasing dependence on international natural gas trading may soon contribute to those tensions. As the world's largest energy consumer, the United States is uniquely sensitive to both environmental and political issues surrounding energy use, and well positioned to impact global energy consumption trends.

There are three basic approaches to decrease fossil fuel consumption in the United States. The most effective method is increasing fuel efficiency. Although efficiency is effective at reducing fossil fuel consumption, some fuel must be consumed, preferably a non-fossil fuel. The second mode of fossil fuel reduction, and most popular, is to find replacements for existing fuels that can leverage the existing fuel infrastructure. Though this approach requires the least infrastructure development, it limits the field of potential replacement fuels. The new fuel must have the same transport, storage, and use characteristics as existing fuels, while being inexpensive enough for the market to adopt.

The third approach to reduce fossil fuel consumption is to match energy supply with demand. There are many energy needs that used fossil fuels simply because they had been the least expensive energy source, not because of its material characteristics. These energy needs can be satisfied by other energy sources, including those with characteristics dissimilar to fossil fuels. Potential new fuels do not have robust infrastructure, and developing that infrastructure can be difficult without an existing demand. Even if new infrastructure develops, it takes time to catch up with the infrastructure developed for fossil fuels. Some potential fuels can overcome these challenges by leveraging other industrial infrastructures that have not historically been used for energy needs. This thesis reviews one such application of matching fuel demand with supply while leveraging existing infrastructure. Specifically, it reviews the use of forestry and agricultural infrastructures to enable solid biomass use for home and commercial heating. All of the technologies considered in this thesis have already been developed, but are not yet integrated into heating systems sufficiently simple and inexpensive to enable large scale adoption.

1.1 Purpose

The United States has chosen biomass as one of the primary alternatives to fossil fuels. Although U.S. biomass resources may seem abundant, they are small relative to the energy consumed each year. These biomass resources must be consumed in a manner that maximizes their environmental and political benefits, which requires high energy efficiency and economic viability. Significant research and subsidization is focused on improving ethanol production from biomass to displace transportation fuels, which are primarily petroleum-based. There are other petroleum uses that may be displaced with biomass fuels that may offer more economic and environmental benefits than corn-ethanol.

This thesis considers the effectiveness of biomass to displace oil currently used in home and commercial heating. The analysis quantifies the energy and economic inputs necessary to cultivate, process, deliver, and finally consume biomass to provide space heating. The results show the total tradeoffs with reference to energy security and environmental effects, including the impact on greenhouse gas emissions, air pollution, and land use change.

Natural gas heating displacement is not considered here for several reasons. First, natural gas is provided automatically from a grid, where it is available. This makes natural gas heating very user friendly. Delivery and metering is automatic, leaving consumers only the task of paying their bill periodically. In contrast, both oil and solid bio-fuel heating requires periodic fuel delivery to an on-site storage tank. Also, natural gas prices are lower than heating oil prices, making the competition more difficult. Finally, oil displacement is a greater factor in energy security than natural gas displacement. Although current technology and pricing makes natural gas relatively immune from competition with solid bio-fuels, future competition may become more likely if these conditions change.

Another fuel alternative not considered in this thesis is unprocessed, raw solid bio-fuels such as wood-chips. Raw bio-fuels are cost competitive in the space heating market if the consumer is near the fuel source, since their low energy density increases fuel transportation costs. Fuel handling automation systems are more complex for raw solid bio-fuel heating systems since there is greater fuel quality variability, e.g. size, shape, moisture content. Heating with raw solid bio-fuels is not considered here due the relatively small market of heating oil consumers that have the required proximity to abundant fuel sources.

The purpose of this thesis is to provide a system level view of biomass-based heating to determine its likelihood for economic success. It also reviews the potential impacts of biomass heating if it displaces a significant portion of the petroleum derivatives heating market. The potential positive impacts reviewed include reduced greenhouse gas emissions and improved energy security through reducing imported petroleum. Negative impacts are also considered, including air pollutant emissions and land use changes. This thesis concludes with recommendations to increase biomass heating system adoption, enhance its positive impacts, and reduce the negative impacts of large scale adoption.

1.2 Bio-fuel History and Current Status

The search for better biomass alternatives begins with an examination of past and current biomass use. The United States consumption history shows which past pressures have led to increased biomass energy use. This analysis includes a corn-ethanol review, since it is the fastest growing bio-fuel segment in the United States. Next, the examination reviews the history of heating with pellets and corns in the United States. Finally, it reviews the solid bio-fuel heating systems used in other nations, reviewing the current state of the art in pellet heating in Europe.

1.2.1 Current United States Biomass Energy Use and Production

Biomass has been used extensively for energy in the United States since its beginning. Wood energy provided most of the energy consumed for the first 100 years of U.S. development. The dominant energy source then became fossil fuels, though biomass energy still remained, as it does today. In 2003, biomass provided 2.8% of the primary energy consumed in the United States, or 2.7 EJ (ExaJoules = 10^{18} Joules) [EIA, 2006]. Wood provided most of this energy, 1.9 EJ [EIA, 2006]. Alcohol fuels provided a relatively small portion, 0.239 EJ [EIA, 2006]. Although wood energy consumption has remained fairly constant recently, corn ethanol consumption has increased at an average annual rate of over 20% [EIA, 2006].

Wood energy is predominantly consumed in the industrial sector, specifically in the wood processing industries [EIA, 2006]. This large consumption rate, 1.53 EJ, comes from a proper matching of fuel supply qualities and demand requirements [EIA, 2006]. The wood and paper industry creates large amounts of waste wood while simultaneously demanding large amounts of process heat, a relatively low quality energy demand. Instead of relying on fossil fuels to provide this heat, they burn their own wood wastes, thus avoiding fuel costs and disposal fees. Industrial wood waste use for energy provides a good example of economic pressures leading to vast bio-fuel adoption, which consumed 98% of mill wastes in 1999 [Walsh, 2000].

Corn-ethanol production warrants special consideration. Although corn-ethanol is not the dominant biomass energy source, its rapid growth suggests that it may become dominant in the near future. It is also the focus of considerable policy debate and relies on corn as its feedstock, one of the fuel alternatives considered in this thesis. Sharing a common feedstock is important since changes in the corn market induced by corn-ethanol subsidies and regulations effects the viability of corn-based heating.

Corn-ethanol is made through the processes of corn saccharification and fermentation. Each bushel of corn produces 2.5 to 2.7 gallons of ethanol [Shappouri, 2002, p2], thus for each GigaJoule of chemical potential stored in corn, at most 0.58 GJ of ethanol is produced. The remaining 0.42 GJ of chemical potential is either wasted or contained in the co-products, such as distillers' grains. As biomass becomes a more significant energy source, supply will become constrained. A supply constrained world must use biomass feedstocks more efficiently to achieve its stated policy goals.

Besides consuming corn in an inefficient manner, corn-ethanol also consumes large quantities of fossil fuel energy. The actual quantity of energy consumed during corn-ethanol production is under constant debate. The net energy balance ranges from -6 MJ/L to 10 MJ/L [Farrell, 2006, p507]. This large fossil fuel based energy consumption makes the net greenhouse gas emission similar to burning gasoline in car engines instead of ethanol, ranging from a 20% increase to 32% decrease in net greenhouse gas emissions [Farrell, 2006, p506]. Corn-ethanol production requires relatively little petroleum, however, consuming 6% to 20% of its energy content [Farrell, 2006, p507]. Using all of the corn production in the United States, 4.5 EJ in 2005 [USDA, 2007], only 2.5 EJ of oil can be displaced, assuming the optimistic case of 58% corn-to-ethanol conversion efficiency and 6% petroleum input.

The United States has also begun to adopt wood-pellet and corn heating, though not as extensively as corn-ethanol. The number of pellet burning appliances sold has increased steadily since 2002, as Figure 1 shows [HBPA, 2007]. This increase in pellet appliance sales corresponds to an increase in pellet fuel sales. The increased fuel demand has recently out-paced supply, causing a dramatic increase in pellet fuel prices [CA, 2005].

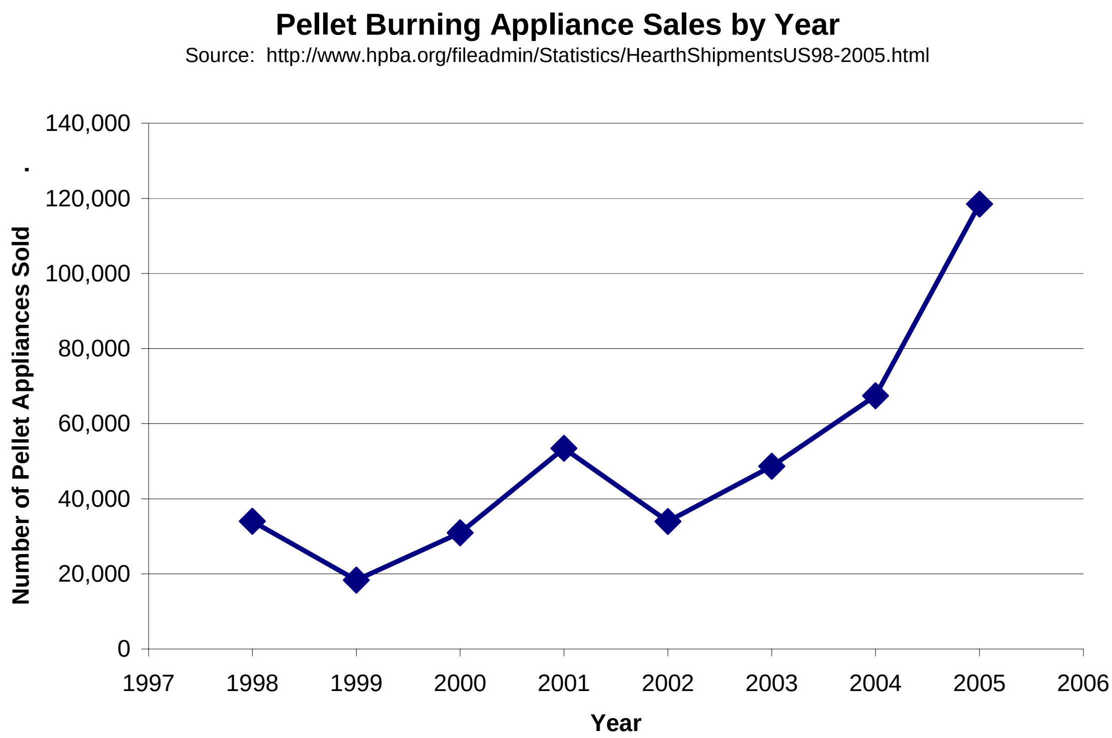


Figure 1: Pellet Burning Appliance Sales from 1998 through 2005. Source [HBPA, 2007]

Most of the pellet appliances currently sold in the United States are pellet stoves. Pellet furnace and boiler adoption, however, is necessary to provide a major fuel switch away from heating oil. Pellet stoves do not integrate into central heating systems and require more manual operation such as fuel filling and ash cleaning, so the total demand for stove heat is less. Central heating systems have only recently entered the United States pellet appliance market. Because this market is young, there is not extensive data on pellet furnace and boiler prices. One current pricing example is the American Harvest Corn/Pellet Furnace (Model # 6100), which provides 75,000 BTU/hour heating and costs $3,300, uninstalled [USStove, 2007]. This price does not include a bulk storage system. Comparable oil furnace prices with 80% annual fuel utilization efficiency (AFUE) are around $1,300 uninstalled, again not including a storage system.

The United States has always relied on biomass fuels, though to varying degrees. Much of the current emphasis on biomass fuel market growth is in transportation fuels such as ethanol. Solid biomass heating systems are also gaining in popularity, though at much smaller scales. Solid biomass heating systems have grown significantly in other nations, however. Following is a brief overview of the status of solid bio-fuel heating outside the United States.

1.2.2 European Solid Bio-fuel Development

Other nations have also been increasing solid bio-fuel heating adoption, specifically Sweden, Austria, and Germany. Regulations and customer preferences in Sweden have created significantly different solid bio-heating technologies than Germany and Austria. Pellet heating system developments in all three nations are significantly different than the pellet heating history in the United States. These differences provide a chance to learn which practices have helped adoption in those nations, and which have hindered adoption and should be avoided. All information in this section on Sweden, Germany, and Austria comes from a pellet heating overview from Frank Fiedler [Fiedler, 2003].

Solid bio-fuel heating in Sweden, Austria, and Germany relies primarily upon wood pellet fuels. Their domestic corn production is too small to allow its use as a fuel. There is also a stronger political resistance to using foods for fuel, relative to the United States. Pellet heating began with simple stove heating, as in the United States, but has already transitioned to furnace and boiler solid bio-fuel heating systems. Figure 2 shows the increase in pellet boilers and heating stoves in the three countries from 1997 to 2001. One of the reasons for a faster adoption of solid bio-heat in Sweden is tax policy that provides preferential economics for pellet fuels. German and Austrian adoption takes place without tax policy induced pricing pressures; though some consumer adoption results from a concern that future tax policies may lead to such price pressures in Germany and Austria. The large environmental niche market in Europe has also led to faster pellet heating system adoption.

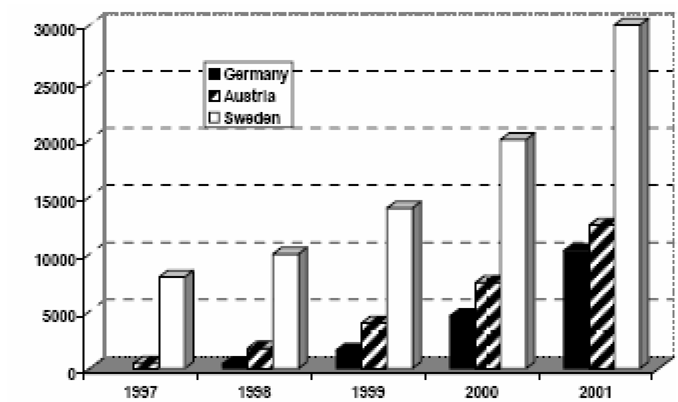


Figure 2: Installed Pellet Boilers and Stoves in One or Two Dwelling Houses in Germany, Austria, and Sweden [Fiedler, 2003, p203]

Swedish boiler technologies are significantly different from German and Austrian technologies. Sweden has two basic boiler design types: two-unit boilers and integrated boilers [Fiedler, 2003, p3]. Two-unit boilers have a modular burner, which is relatively simple to replace. This modularity is one reason pellet burners are more prevalent in Sweden, since the cost of retrofitting old oil burners with new pellet burners is significantly less than installing completely new systems. Sweden also has integrated boilers. These integrated systems provide greater efficiency and lower pollution since the entire system is optimized for pellet fuels. In general, Sweden uses less costly technology and offers fewer options on their heating systems relative to Austria and Germany.

German and Austrian solid bio-heating systems are more complex and costly than their Swedish counterparts. Their heating systems are more user friendly, offering automated fuel handling, cleaning, and ash compaction. They also have more aesthetic features, further adding to the cost. Figure 3 shows a comparison for costs and features between Swedish and Austrian boilers. Note that the currency is in 2003 Euros. Comparable values in 2005 U.S. dollars are $4,806 to $7,210 for Swedish boilers and $8,411 to $12,016 for Austrian boilers. It is worth noting that boilers are generally more expensive than forced-air furnaces, which are more common in the United States.

Property	Swedish boilers	Austrian boilers
Type	two unit boiler	integrated boiler
Power modulation	50%/100%	30-100%
Boiler efficiency	78-85%	86-94%
Combustion air supply	blower	aspirator
Combustion control	no	no/lambda/speed controlled fan
Lighting	automatic	automatic
Air- passages cleaning	manual	automatic, optional
Cleaning burner	manual	automatic, optional
Ash removal from combustion chamber	manual	automatic, optional
Time interval ash re-moval from ash pan	weekly	2…8-times per year
CO emissions [mg/m^3]	260-650	12-250
Price	4000-6000 Euro	7000-10000 Euro

Figure 3: Cost and Feature Comparison of Swedish and Austrian Boilers [Fiedler, 2003, p208]

All three countries regulate pellet combustion emissions through heating system regulations and fuel regulations. Emissions enforcement mechanisms include incentive programs and mandated testing for compliance. Incentive programs include the German government's program that provides furnace subsidies only for furnaces that meet emissions standards. A sample of German, Swedish, and Austrian emission limits is shown in Figure 4. Besides the government regulations, these nations also have standards and certifications from non-governmental entities, such as the Swedish

National Testing And Research Institute. These non-binding certifications increase the product brand strength, improving their retail sales.

Regulation	Supply	Nominal Power kW	Limit value for emission CO	OGC	Dust
			mg/m^3 dry flue gas with 10 vol-% O_2, 0°C, 1013 mbar		
EN 303-5 (valid since 1999)	manual	<50 kW	5000	150	150
	automatic	<50 kW	3000	100	150
Swedish Boverket	manual & automatic	<50 kW	2000	150[1] / 250[2,3]	100
German Federal Ministry of Economics and Labour[3,4] (guideline)	manual & automatic	< 15 kW	250[5]/ 500[6]	-	50
Bundes-Immissionsschutzgesetz – BimSchV [3,7]	manual & automatic	15 kW-50 kW	4000	-	150

[1] for pellet boiler
[2] for pellet heating stoves
[3] limit values are defined for 13 vol-% O_2 in the dry flue gas
[4] Boiler efficiency has to be minimal 85 %
[5] nominal load
[6] low load
[7] no regulation for boiler/stoves smaller 15 kW

Figure 4: Pellet Heating Regulations and Guidelines for Sweden, Austria, and Germany [Fiedler, 2003, p215]

Many nations are considering solid bio-fuels for heating. The demands for heating systems differ, making common multinational furnace and boiler design difficult. For example, the available fuel types, governmental regulations, and aesthetic demand vary by country, region, and culture. However, these differences also increase the range of engineering and policy learning, allowing other nations to leverage this experience as needed to provide the lowest cost and most adoptable solid biomass heating systems.

1.3 Methodology

One of the most important aspects of this analysis is to provide consistent comparisons. Information from many sources was compiled in this thesis, creating a need for many conversions and adjustments. The following section describes the conversion and adjustment methods used to provide the consistency necessary to make more meaningful comparisons.

1.3.1 Heating Values

Bio-fuel energy contents used in this thesis are compared as higher heating values (HHV). Higher heating values differ from lower heating values (LHV) by including the heat of phase transformation released during water vapor condensation. Some high efficiency furnaces extract this condensation energy from the exhaust gas, making it appropriate to use the HHV. LHV use could result in some reported furnace efficiencies over 100%. Higher heating values are typically 6-7% higher than lower heating values for biomass feedstock [ORNL, 2006]. Because the biomass fuels may vary considerably in chemical composition, a robust analysis to calculate the difference between HHV and LHV is difficult. All conversion calculations assume the average increase from LHV to HHV, 6.5%, for simplicity and consistency.

1.3.2 Dollar Discounting

Energy supply economics are a significant factor in public adoption rates. A valid economic analysis must consider the time value of money, both into the future and from the past. The references for establishing cost of materials and processing were compiled at different times, and must be normalized for an effective analysis. All monetary values are translated into 2005 dollars using the Bureau of Labor Statistics Consumer Price Index [BLS, 2007]. Only average annual values are used.

Monetary values from some references explicitly state the year the value is established. When the date of the monetary values is not explicitly given this analysis assumes the year of publication to be the date of valuation. Although this assumption is unlikely to be true, it is a consistent formulation for comparisons and will likely be close to the actual date of valuation.

1.3.3 Currency Conversion

Many of the references are from international publications, thus requiring currency conversion to maintain monetary consistency. This currency conversion is based upon average valuation for the year of data explicitly stated, or year of publication. This value is then adjusted to 2005 dollars by the inflation technique discussed above. All currency conversions were performed using the historical currency exchange rate calculator provided by Oanda using the interbank rate [Oanda, 2007].

1.3.4 Fossil Fuel Carbon Emissions

Fossil fuels are an integral part of the current global economy. Any economic activity inherently consumes fossil fuels, such as harvesting, processing, and transporting non-fossil fuels. Fossil fuel combustion releases carbon dioxide into the atmosphere; therefore any renewable energy that relies on the existing energy infrastructure inherently releases some fossil fuel CO_2 as well. The following section describes the fossil fuel carbon emissions rates assumed for each fuel type. It also reviews the fuel make-up assumption for some secondary energy sources, such as electricity, and their corresponding carbon dioxide emissions.

Coal has the greatest carbon dioxide emissions per unit of energy, between 24 and 27 kg-C/GJ (kilogram of Carbon emitted as CO_2 per GigaJoule of chemical potential energy in the coal), depending upon the coal type. For example: bituminous coal releases

24.1 kg-C/GJ, sub-bituminous coal releases 24.9 kg-C/GJ, and lignite emits 25.2 kg-C/GJ [EIA, 2006F]. The current mix of coal types used for electricity production in the United States has an average CO_2 emission rate of 24.6 kg-C/GJ [EIA, 200].

Oil derivatives produce less carbon dioxide per unit of energy released. Oil derivative CO_2 emissions depend upon the fuel type. The carbon emissions rates for some petroleum derivatives include: 18.3 kg-C/GJ for gasoline, 18.9 kg-C/GJ for diesel fuel, and 16.3 kg-C/GJ for propane [EIA, 2006F]. This analysis is concerned primarily with diesel fuel emissions, since diesel is the dominant fuel used in agriculture and bulk transportation.

Natural gas emits the least carbon dioxide per unit of energy of any of the fossil fuel types. The average net CO_2 emission for pipeline natural gas is 13.7 kg-C/GJ [EIA, 2006F]. Though this analysis does not consider natural gas heating displacement, this value is needed for calculating electricity emissions rates, since natural gas consumption provides a significant portion of the electricity in the United States.

Electricity is a secondary energy source, thus CO_2 emissions depend upon: the fuel mixture used to produce electricity, conversion efficiencies, and transmission losses. The assumed fuel mixture is based upon the 2005 United States electricity production mix [EIA, 2006E, p1]. Coal-based electricity generation provided 49.7% of U.S. electricity generation in 2005. Petroleum was rarely used for electricity generation, comprising only 3% of the market. Natural gas had a much larger portion of the market at 18.7%. The remaining electricity production was from nuclear, hydroelectric, and other sources, mostly renewable. Those sources were assumed to be carbon-neutral for this calculation. The net carbon emission rate for electricity production was 51.1 kg-C/GJ, assuming 30% electricity conversion and distribution efficiency.

1.3.5 Thesis Chapters

The following chapters provide a solid bio-fuel heating overview and analysis. Chapter 2 reviews the raw biomass resources available and the economic and energy costs associated with their cultivation and harvest. Chapter 3 analyzes the costs associated with transforming the fuel into a more usable form and distributing that refined fuel. Chapter 4 reviews combustion technologies and effects, such as pollution. Chapter 5 examines the economic, environmental, and political context of solid bio-fuel heating more closely. This examination includes small scale effects on the consumer as well as larger national and global scale effects. Finally, chapter 6 summarizes the results and provides some recommendations to improve total system efficiency and consumer adoption rates. Throughout the thesis, technologies that are currently available in other countries or industries are recommended for inclusion in the large scale bio-fuel heating system, when it appears the industry could benefit from leveraging such technologies.

2 Raw Biomass Resources

The first step towards identifying viable biomass energy use is finding the appropriate feedstock. Feedstock selection impacts the total available energy quantity, costs, and infrastructure change requirements. Chapter two considers three basic biomass feedstock types: wood waste from forest residue, the energy crop switchgrass, and field corn (kernels). Each feedstock has advantages and disadvantages relative to the others, suggesting that a mixture of feedstocks may be optimal.

2.1 Raw Biomass Resources – Wood

Wood provided the first dominant energy source for early societal development. Wood fuels provided abundant, relatively dense, and easy to handle energy for heating, cooking, and some industrial processing. Some nations still rely heavily on wood for their energy needs, though trees are often harvested in unsustainable manners. This section focuses on sustainable wood and wood waste harvesting in the United States.

Modern economies transitioned away from wood energy as lower cost fossil fuels became more accessible. Fossil fuels offered higher energy density, greater uniformity, simplified handling, and ultimately lower cost than wood could offer. Figure 5 shows the dominant energy source in the United States transition from wood to fossil fuels. The figure also shows that around 1975 wood energy consumption began to increase, suggesting that increasing wood fuel use can be a part of a modern economy when fossil fuel energy prices increase.

Wood resources must have competitive material and economic properties to compete as a viable energy source. The following sections review the properties, costs, and environmental aspects of wood-fuels, as well as the quantity available in the United States.

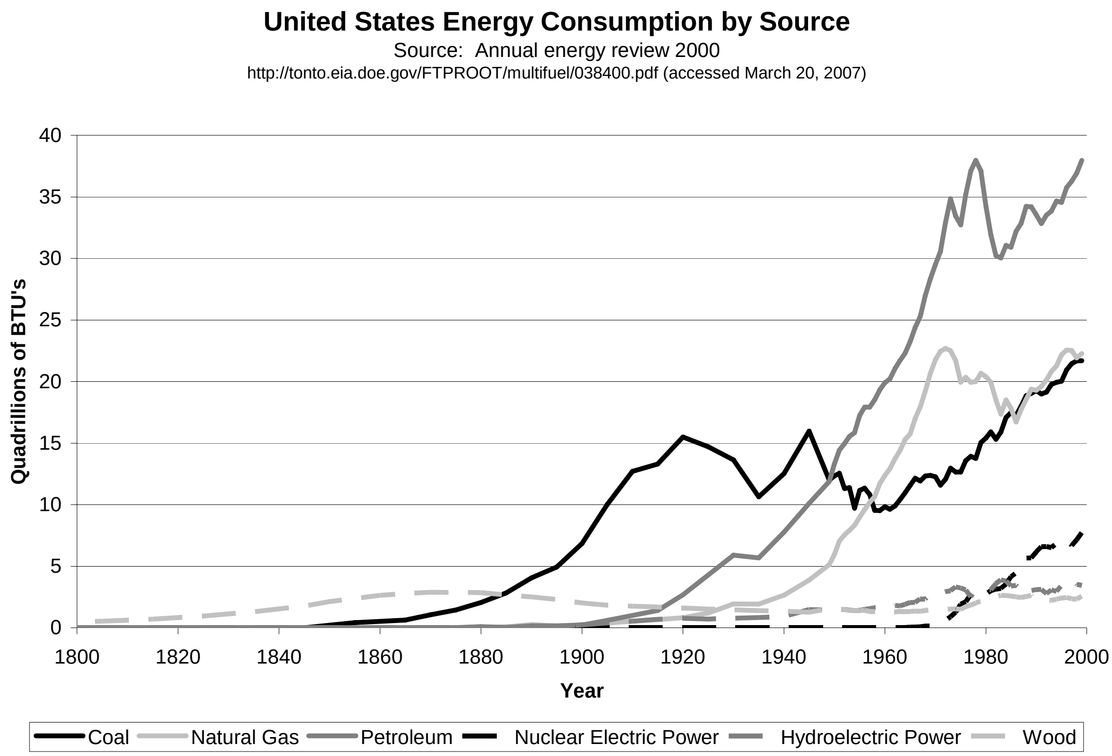


Figure 5: United States Energy Consumption By Source (Quadrillions of BTU's) [AER, 2001, pp353-354]

2.1.1 Properties

Raw feedstock properties impact the viability of any potential new fuel development. This section reviews the properties of wood as a bio-fuel. Raw wood properties vary depending upon the species of tree. For example, faster growing softwoods generally have a lower energy density and higher ash content than hardwood trees. Table 1 contains the energy and ash contents of several types of biomass, including a variety of wood types.

Properties of selected biomass materials (wt%)

Material	Moisture content (%H_2O)	HHV[a] (MJ/kg)	FC content (%)	VM content (%)	Ash content (%)	Alkali metal content (as Na and K oxides) (%)
Fir	6.5	21	17.2	82.0	0.8	–
Danish pine	8.0	21.2	19.0	71.6	1.6	4.8
Willow	60	20.0	–	–	1.6	15.8
Poplar	45	18.5	–	–	2.1	16
Cereal straw	6	17.3	10.7	79.0	4.3	11.8
Miscanthus	11.5	18.5	15.9	66.8	2.8	–
Bagasse	45–50	19.4	–	–	3.5	4.4
Switchgrass	13–15	17.4	–	–	4.5	14
Bituminous coal	8–12	26–2	57	35	8	–

[a] Dry basis, unless stated otherwise.

Table 1: Variations in Biomass Properties by Type [McKendry, 2002, p43]

Table 1 shows wood energy densities between 18 and 22 GJ/dry-ton, with ash contents varying between 0.8% and 2.1% by mass. Future calculations use the simplifying assumptions that wood energy density and ash content are in the middle of their ranges, 20 GJ/dry-ton and 1.5% by dry-weight, respectively.

The material properties considered so far do not change with processing. High grade wood leaves the forests as logs, which are valuable in industries such as construction and furniture making. This high-value wood product is later processed, producing wastes such as shavings and sawdust that can provide low-cost energy. Lower value wood consists of forest residues such as logging residues and rough, rotten, and salvageable dead trees. Pole-wood and saplings are assumed to be left in the forest to grow for future harvests [Walsh, 2000]. This lower value wood is left in the forest to decompose, or is chipped to simplify handling for extraction. Most of this forest residue is currently underutilized as a potential bio-fuel source.

Wood chips have low bulk energy density due to their loose packing and porous nature. The bulk mass energy densities vary between 0.18 and 0.23 dry-tons/m^3 [McKendry, 2002, p44]. Assuming a mass energy density 20 GJ/dry-ton and bulk mass volumetric density of 0.20 dry-ton/m^3, wood chip bulk volumetric energy density is 4 GJ/m^3, which will be used in all future calculations.

2.1.2 Quantity of Wood Available

Most alternative energy sources share a common problem, scalability. The total resources available are rarely sufficient to significantly affect the markets addressed. A 2000 assessment of available United States biomass resources, conducted by the Oak Ridge National Laboratory, reviews the total energy available from a variety of biomass sources in the United States. This analysis considers the costs, including initial processing and bulk delivery. The two wood fuel types considered were mill wastes and forest residues. Mill wastes are not included in this analysis since 98% are already used to produce energy and wood products, such as pressboard [Walsh, 2000]. At $3.20/GJ, there are approximately 0.9 EJ of energy available, slightly less than the 0.98 EJ of heating oil consumed in the United States in residential and commercial buildings [EIA, 2001, Table CE1-1c][EIA, 2006A, Table C1]. The feedstock price includes: collection, harvesting, chipping, loading, hauling, and unloading costs, a stumpage fee, and a return for profit and risk [Walsh, 2000].

Walsh describes the maximum amount of forest residue available for fuel production at state-level resolution. Wood-fuel's low energy density, relative to fossil fuels, causes transportation costs to increase the fuel price and decrease energy efficiency. Thus, the final analysis must consider the quantity available in each region, since cross-country transportation costs would be substantial. Table 2 shows the forest residues available by region.

Forest Residue Energy Available By Region at $3.20/GJ		
Region	**Sub-Region**	**Energy (petaJoules)**
Northeast	New England	64
	Middle Atlantic	73
Midwest	East North Central	76
	West North Central	43
South	South Atlantic	193
	East South Central	126
	West South Central	95
West	Mountain	82
	Pacific	145

Table 2: Regional Energy Resources from Forest Residue [Walsh, 2000]

2.1.3 Energy Consumed During Wood Harvest and Transportation

Although there are considerable wood resources available, extracting those resources consumes energy. The following section describes the amount of energy consumed to provide chipped wood fuel to a centralized location including: harvesting, chipping, and transportation.

Forest residue collection first requires raw material harvesting. Much of this material, such as stripped limbs, will be available at the logging deck already, where chipping and truck loading take place. Harvesters must collect some materials from the forest, such as dead trees, that are not otherwise gathered. The area serviced by a logging deck is approximately 20 acres, or 0.081 km^2, making transportation less than one half of a kilometer. Even assuming that dead wood gathering consumes five times the energy consumed in trucking freight [Muster, 2000, p11] the total energy consumption per unit bio-fuel energy is less than 0.1% of the wood's energy content, a negligible quantity.

Once the raw wood is gathered at the logging deck, it must be chipped to simplify wood handling and storage. Wood may also require debarking, depending upon the fuel quality required. Bark contains significantly more incombustible minerals, having ash contents roughly ten times greater than cleaned wood [Polagye, 2005, p 4]. This high ash content makes bark less suitable as a fuel and more desirable to leave behind due to its higher nutrient content. Together, wood chipping and debarking consumes 28.2 kW-hr/dry-ton [Polagye, 2005, p37]. Assuming a 30% power conversion efficiency using a diesel engine, this translates to 0.017 GJ_{Diesel}/GJ_{Wood}.

Finally, harvesters must transport the wood chips to a centralized processing facility. The expected transportation distance between the logging deck and the fixed processing facility is 80 km [Polagye, 2005, p121]. Transportation consumes 0.029 GJ_{Diesel}/GJ_{Wood}, assuming that raw chips have 50% moisture content.

2.1.4 Environmental Impact

Using wood as an energy source creates considerable controversy. Wood harvesting has shown both ecological harm and benefits. History has shown that consuming wood for fuel can be devastating to the ecology since the time for forest re-growth is so long. In some cases recovery is impossible, such as when a species dependent upon the forest becomes extinct. Old-growth forests are inherently harmed by any act, except possibly dead-wood thinning to reduce fire hazards.

Regulated wood harvesting, however, may benefit forest quality. Using waste wood for fuel inherently increases the value of a forest, encouraging more active management for commercial forests which can improve the quality of existing commercial forests. Increased wood harvesting profitability requires strong forest protection regulations to precede extensive wood-fuel use to counter the increased pressure to expand wood harvesting into non-commercial forests.

Wood energy has ecological benefits from reducing net greenhouse gas emissions. Wood derives its carbon from the atmosphere, and thus is deemed carbon neutral. The process of harvesting the wood, however, consumes power generally provided by fossil fuels. Table 3 shows that 0.869 kg/GJ_{wood} of fossil fuel based carbon dioxide is emitted during harvesting.

2.1.5 Summary of Wood as Raw Fuel

Wood was once the fuel of choice for the United States. As fossil fuel prices increase, wood may become an important energy source once again. Potential environmental benefits from wood combustion are significant, such as reducing carbon dioxide emissions into the atmosphere. Unfortunately, those benefits are closely coupled to opportunities for abuse if logging is not regulated. Table 3 summarizes the energy efficiencies, carbon emissions, and economic costs of collecting forest residues for fuel.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Biomass	Coal	Oil	Gas	Net	
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9

Table 3: Summary of Economic, Energy, and Carbon Costs for Forest Residue Collection

2.2 Raw Biomass Resources – Switchgrass

Biomass pellet producers use primarily wood as their feedstock. However, only certain regions have access to ample wood resources, leading to a search for viable alternatives. Many biomass fuel types can be considered: field residues such as corn stover, construction/demolition waste, or other short rotation energy crops such as hybrid willows. This section reviews switchgrass since it was deemed the most economically viable energy crop by a 1999 ORNL study [Walsh, 2000], detailing properties of switchgrass, costs associated with growth and harvest, and environmental impacts.

2.2.1 Switchgrass Properties

Switchgrass is a perennial warm season grass native to North America. There are two basic types of switchgrass. Lowland switchgrass is the taller variety with a height greater than three meters that is accustomed to wet soils and often found in the South. Highland switchgrass is shorter, adapted to drier soils, and more commonly found in the Great Plains. Because switchgrass is a native grass, it is more resistant to disease and better adapted to grow in what would otherwise be marginal lands relative to conventional crops such as corn or wheat. Switchgrass reproduces by two means: rhizomes[1] and seed. Rhizome reproduction takes place in mature stands and provides robust switchgrass fields that can compete with other plant species. New fields, however, must be established through seeds. Switchgrass takes three years to mature from seed, and is more vulnerable to weeds and insects while immature. This aspect makes old field maintenance simple, but adds difficulties to establishing new fields. [McLaughlin, 1999]

Warm-season grasses such as switchgrass have reduced ash content relative to other, cool-season grass types. Table 1 shows that switchgrass typically has a 4% ash content, by dry mass. The energy density is about 17 MJ/dry-kg, 15% less than wood energy density. The higher ash content and lower energy density make switchgrass less desirable than wood, but switchgrass is easier to dry and complements wood in regional availability.

[1] Rhizome reproduction takes place when a mature, or partially mature, plant grows a reproductive shoot, or rhizome, that is used to start a new plant nearby. This reproduction technique allows the nutrient gathering capabilities of the adult plant to assist in the new plant's development. Rhizome reproduction leads to very dense fields, often crowding out any competing weeds, and is commonly found in grasses.

2.2.2 Quantity of Switchgrass Available

Although switchgrass is often mentioned as a viable energy crop, very little of it is currently produced. Existing production is used for animal feed or soil conservation, since an energy market for switchgrass has not yet developed. The ORNL analysis of bio-fuel availability included the potential switchgrass production at different pricing points. They calculated that 3.3 EJ could be produced at prices of $3.50/GJ. As with wood, production varies by region. Table 4 shows the expected production capabilities by region.

Switchgrass Energy Available By Region at $3.50/GJ		
Region	**Sub-Region**	**Energy (petaJoules)**
Northeast	New England	19
	Middle Atlantic	118
Midwest	East North Central	654
	West North Central	1,460
South	South Atlantic	269
	East South Central	608
	West South Central	571
West	Mountain	66
	Pacific	0

Table 4: Potential Switchgrass Derived Energy by Region at $3.50/GJ [Walsh, 2000]

2.2.3 Switchgrass Harvesting Costs

The economic costs for switchgrass cultivation and harvesting depend upon many factors, including the local growing environment and land value. Walsh et al. estimate that over 3 EJ are available at a net cost of $3.50/GJ.

As with wood-energy, cultivating and harvesting switchgrass also requires other sources of energy. The estimated energy consumed during cultivation, harvest, and transportation is 7% of the bio-energy output [Jannasch, 2001, p 3]. Switchgrass cultivation requires little to no fertilizer, pesticide, and herbicide application. The energy consumed is assumed to be consumed primarily diesel fuel used by harvesting and transportation equipment.

2.2.4 Environmental Impact

One of the greatest reasons to transition to switchgrass for energy is its impact on the environment. Although switchgrass planting may lead to monoculture issues of reduced bio-diversity, its use increases crop diversity relative to today and is a closer approximation to the native prairie environment. Switchgrass benefits include: soil and water conservation, wildlife habitat provision, and carbon capture and sequestration.

First, planting fields to switchgrass has similar effects to the perennial grasses that reside on CRP land, or Conservation Reserve Program. The undisturbed root structures reduce soil erosion from wind and water. Slowing water run-off also increases the land's ability to capture more moisture into the ground. Also, the no-till nature of perennials eliminates moisture losses from regular tilling. Land enrolled in CRP also creates more habitats for wild creatures. The grasses grow densely, providing more protection for small animals relative to the less dense row crops common today. Planting fields of switchgrass in the Great Plains is similar to re-establishing the old Plains ecosystems that existed before tilled crops replaced native grasslands.

Finally, switchgrass has an exceptionally deep root structure, around 3 meters. This deep root not only provides the erosion protection mentioned before, but sequesters carbon underground that was originally captured by its leaves from the air. Figure 6 shows that grasslands hold over 14 times more carbon than conventional cropland. The figure also shows how rapidly switchgrass is able to sequester carbon in the ground.

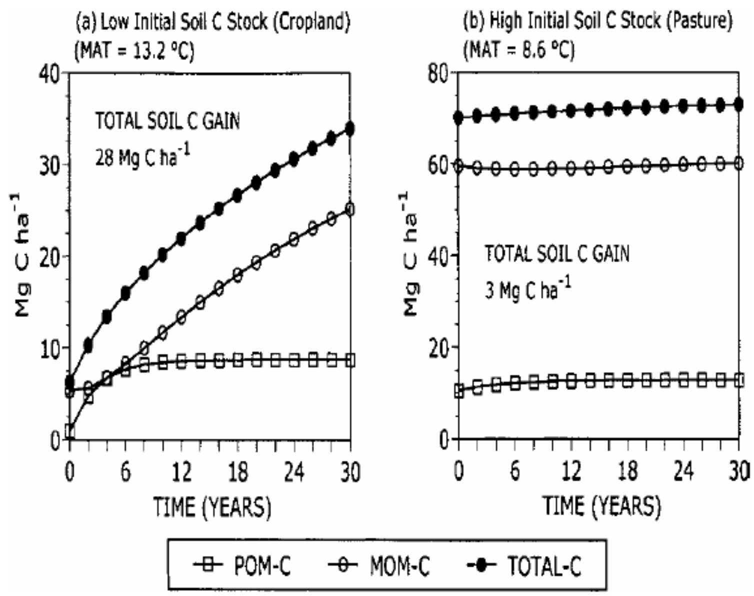


Figure 6: Changes in Soil Carbon Levels after Switchgrass Introduction. POM refers to Particulate Organic Matter and MOM Refers to Mineral-Associated Organic Matter. Note the Differences in Ambient Temperature. [McLaughlin, 2002, p2125]

2.2.5 Summary of Switchgrass as Raw Fuel

Switchgrass offers many positive externalities in the environmental realm. This paper does not quantify the externalities, but does consider the internal economic effects of production. Not including externalities, switchgrass as a fuel is not as attractive as forest residues but increases the areas of biomass availability since it is economically competitive in many regions where large commercial forests are non-existent. Table 5 shows the energy and economic costs associated with switchgrass and forest residues.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Biomass	Coal	Oil	Gas	Net	
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3

Table 5: Summary of Economic, Energy, and Carbon Costs for Switchgrass Harvesting

2.3 Raw Biomass Resources – Corn

Section 2.3 considers using corn for fuel, an abundant crop that is generally used for animal feed. Consuming feed-corn as fuel-corn creates considerable social discomfort and controversy since it directly impacts the world's food supply. One common misconception is that most feed-corn is directly consumed by humans. In the United States, field corn is used primarily as cattle feed and artificial sweeteners, unlike sweet corn, which is intended for direct human consumption. Some feed-corn, however, is used to produce cornmeal and other direct consumables, making the human food supply costs sensitive to feed-corn pricing. Feed-corn is already used in ethanol production, so it is evaluated here to determine if there is a better use for this limited resource.

The main reasons that corn is used for fuel in the United States are its abundance and low cost. Table 6 compares the relative abundance and costs of some grains grown in the United States, showing that corn at the 2005 average price of $1.90/bushel is the most abundant and lowest cost grain produced in the United States.

2005 United States Grain Production		
Commodity	**Production (million tons)**	**Cost ($/ton)**
Corn	282	$ 74.80
Oats	2	$ 108.85
Wheat	57	$ 124.93
Rice	10	$ 171.96
SoyBeans	83	$ 202.09
Sunflowers	2	$ 253.53

Table 6: Sample of 2005 Grain Production and Prices in the United States [USDA, 2007]

The United States does not have as strong of a history using corn for fuel as it does with wood. The fact that corn is now being viewed as an energy source is explained by the history of its economics. Figure 7 shows that corn prices have historically been higher than heating oil prices, when normalized by inflation and energy content. It also shows that agricultural efficiencies have driven down the cost of corn, while oil prices have stayed remarkably flat.

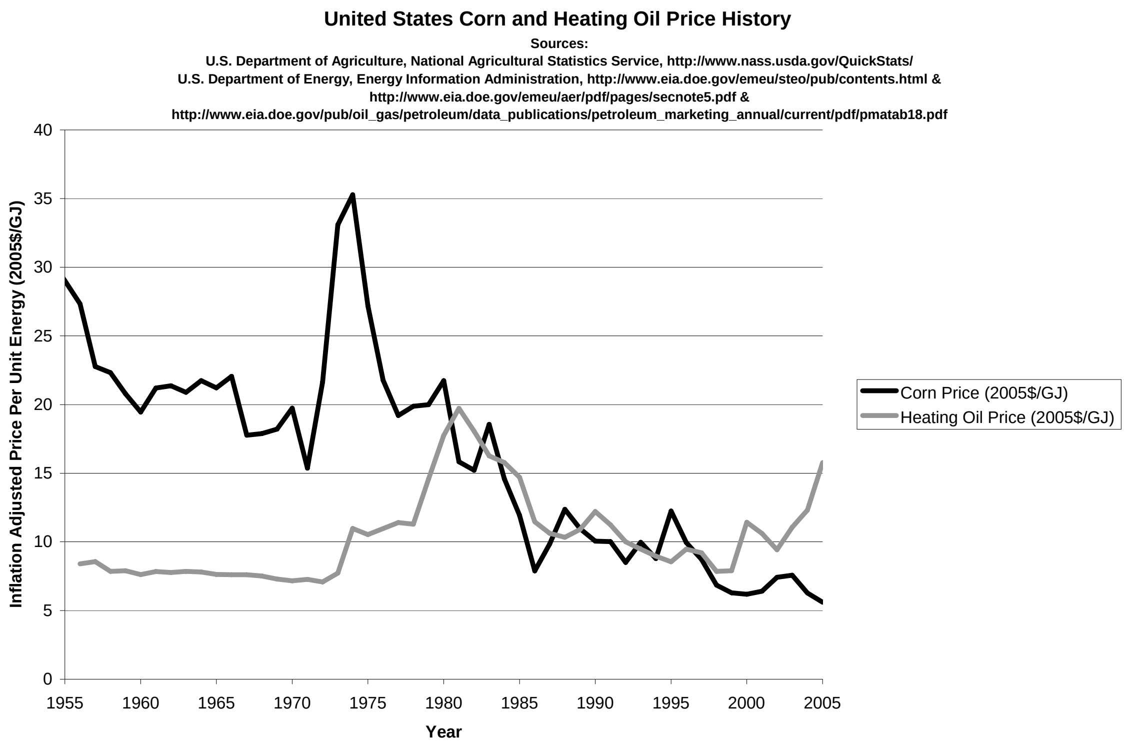


Figure 7: United States Price Histories for Corn (Average Paid to the Producer) and Retail Heating Oil [ERS, 2007C][EIA, 2006C]

2.3.1 Corn Properties

Corn must have suitable physical and chemical properties to be considered a viable fuel. The following paragraphs describe some of the more critical fuel properties for field-corn, including energy density, ash content, and moisture content. Note that only field-corn kernels are considered here, not corn cobs stover. Kernels are naturally available in a “pelleted” form; thus the mechanized pelleting step required by the other feedstocks is not required. In contrast, corn cobs and stover are not regularly harvested and transported, and so are not considered due to their lack of available infrastructure.

Like most biomass types, corn has an energy density near 20 GJ/dry-ton. The average bulk volumetric energy density of corn with a 15% moisture content is 13.4 GJ/m^3, while its mass energy density is 16 MJ/kg [Patzek, 2004, p27], roughly 18.75 GJ/dry-ton. Moisture contents may be as low as 10%. If corn moisture content exceeds 15%, the grain is generally dried before shipment.

2.3.2 Quantity of Corn Available

As Table 6 shows, corn is the most abundant grain grown in the United States. At 16 GJ/ton, the total energy available in the form of corn in 2005 was 4.57 EJ. Some of this total production must be available to the existing feed industry to maintain the domestic agricultural market. In 2005, 1.6 billion bushels were used in ethanol production [ERS, 2007C, Table 31], and 2.15 billion bushels were exported [ERS, 2007C, Table 4], for a total energy value of 1.4 EJ. Corn production is not evenly distributed across the United States. Table 7 shows the price and quantity of corn produced in 2005 in terms of energy content.

Corn Energy Available By Region			
Region	**Sub-Region**	**Energy (petaJoules)**	**Average 2005 Fuel Cost ($/GJ)**
Northeast	New England	0	-
	Middle Atlantic	75	$5.57
Midwest	East North Central	1,553	$4.91
	West North Central	2,485	$4.67
South	South Atlantic	111	$5.42
	East South Central	125	$5.35
	West South Central	129	$5.84
West	Mountain	72	$5.64
	Pacific	18	$6.65
National Total		4,569	$4.86

Table 7: Corn Energy Availability and Cost by Region [USDA, 2007]

2.3.3 Corn Cultivation and Harvesting Costs

This section considers the economic and energy costs associated with corn production. This analysis assumes that economic costs are reflected in the spot price. Since corn production is not evenly distributed across the U.S., corn must be transported from major production locations to major consumption locales, resulting in price differences in different regions, as shown in Table 7.

Corn cultivation and harvesting requires considerable energy relative to wood and switchgrass, as the summary for this section will describe. The recent research emphasis on energy balances for corn based ethanol provides extensive and closely scrutinized data for cultivation energy consumption. A summary analysis from the USDA shows that cultivation, harvest, and transportation for corn consume approximately 0.153 GJ_{in}/GJ_{corn} [Shappouri, 2002, p7]. The fossil fuel inputs are as follows: 0.079 GJ_{oil}/GJ_{corn}, 0.054 GJ_{NG}/GJ_{corn}, and 0.020 GJ_{coal}/GJ_{corn}.

2.3.4 Environmental Impact

Fuel-corn production has several significant environmental disadvantages. The major environmental disadvantage is the dependence of corn agribusiness on chemicals and irrigation. Much of the increasing yield shown in Figure 8 results from this increased use of chemicals and irrigation. Chemicals such as fertilizers, pesticides, and herbicides can damage the surrounding environment, while irrigation draws down water tables and may not be sustainable in certain regions.

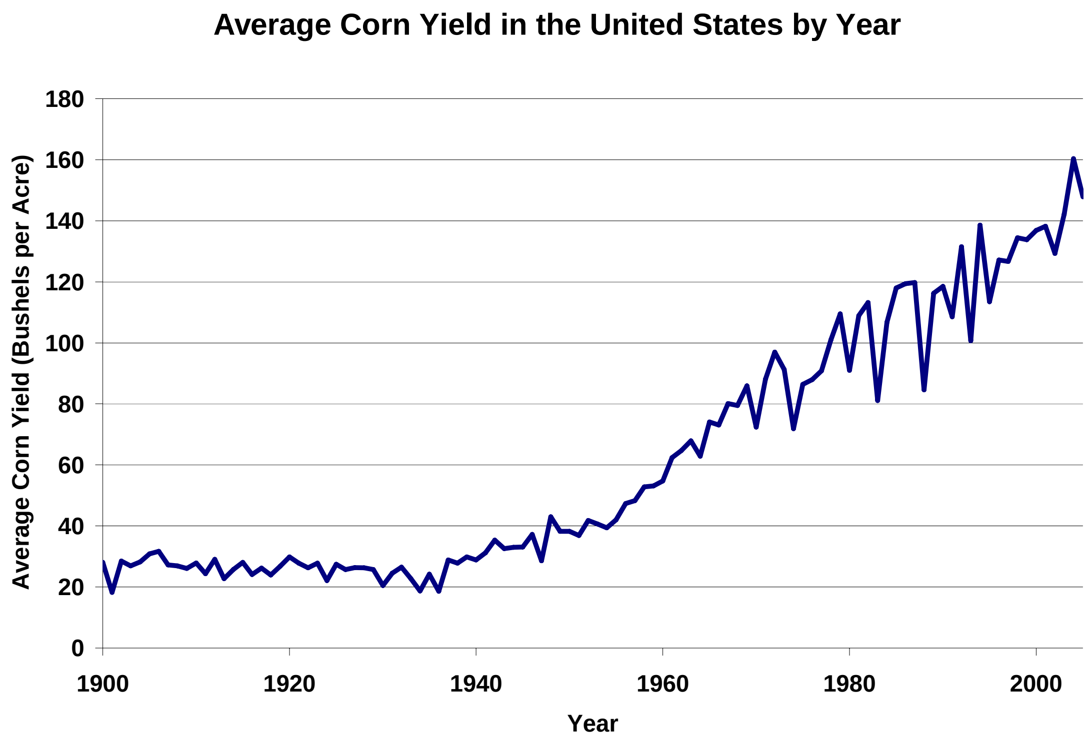


Figure 8: History of Average Corn Yield in the United States [USDA, 2007]

The negative environmental effects of fuel-corn complicate some of its environmental benefits. Although corn combustion itself is CO_2 neutral, the high energy intensity of corn cultivation and harvest makes its effective CO_2 emissions higher than other bio-fuel feedstocks. Table 8 shows that each GigaJoule of thermal energy from corn releases 3.3 kg of carbon from fossil-fuels into the atmosphere. Although fuel-corn emits low amounts of net CO_2 to the atmosphere relative to fossil fuels, its reduced ability to sequester carbon in the soil relative to grasslands is the cause of some concern. As Figure 6 showed, normal cropland holds less carbon in the soil than grasslands. As fuel-corn popularity increases, CRP land is likely to be converted to tilled cropland, causing net atmospheric CO_2 increases due to land use changes.

2.3.5 Summary of Corn as Raw Fuel

Corn is a cost effective energy source that is currently available in large quantities. This has not always been the case, but over time, corn prices have decreased faster than oil prices. Table 8 shows that the net CO_2 emissions from fuel-corn are more than twice the emissions from either forest residue or switchgrass. In summary, although corn may be cost effective as a fuel and available in the greatest quantities, it is not as inexpensive or environmentally friendly as either forest residues or switchgrass.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Biomass	Coal	Oil	Gas	Net	
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Corn	$4.62	4.51	0	0.022	0.085	0.058	0.165	2.9

Table 8: Raw Feedstock Summary Table

2.4 Feedstock Summary

This chapter has considered three feedstock types: wood, switchgrass, and field-corn kernels. Each feedstock is available in sufficient quantities to significantly impact the United States heating oil market, but vary significantly in regional availability, properties, and costs.

Regional availability is critical since all biomass resources have lower energy density than fossil fuels, thus making transportation costs higher. Wood resources are generally available where corn and switchgrass resources are not, and vice versa. Table 9 shows the cumulative biomass resource available by region.

Biomass Energy Available By Region and Feedstock		
Region	**Sub-Region**	**TotalSolid Bio-Fuel Supply (PJ)**
Northeast	New England	83
	Middle Atlantic	266
Midwest	East North Central	2,283
	West North Central	3,988
South	South Atlantic	573
	East South Central	859
	West South Central	795
West	Mountain	220
	Pacific	163

Table 9: Wood, Switchgrass, and Corn Energy Available by Region

Wood fuels have the highest energy density on a dry mass basis, but also have the highest inherent moisture content. This makes early stage transportation more expensive for wood, but dry transportation less expensive. Wood and corn provide the lowest ash content, which is beneficial in solid combustion furnaces.

Feedstock production economic costs favor wood and switchgrass use, since they are 30% less expensive than corn. Wood wastes become available at very low costs, since wood wastes are already produced and inexpensive to gather in some regions. The negative impact of corn's higher cost is partially offset by its robust transportation infrastructure, and pre-pelleted form, making it useable as a fuel fresh out of the field.

Feedstock production energy costs also favor wood use. Wood consumes the least fossil fuels of the three feedstocks, roughly 30% less than switchgrass production and 70% less than corn production. The reduced fossil fuel consumption leads to wood having the lowest net CO_2 emissions of all of the feedstocks.

Environmental externalities vary considerably by feedstock. Wood waste consumption can have very few negative environmental externalities if properly regulated. Increasing forest product values can increase the pressure to use old-growth forests, which may negatively impact biodiversity. The commercial pressure to use old-growth forests must be countered by stronger protective regulation.

Switchgrass production would displace existing tilled annual crops, providing a net environmental benefit due to its water and soil conserving properties. Switchgrass also sequesters more carbon in the ground since it is a perennial with large root structures.

Corn is the least environmentally favorable option. Corn cultivation has a higher energy and chemical intensity relative to wood and switchgrass. Corn production also holds less carbon in the ground, so as CRP land becomes converted to corn production there will be carbon releases greater than those expected from fossil fuel combustion alone.

This chapter has shown the basic properties of low-grade bio-fuel feedstock production, which are important for later calculations. These properties are summarized in Table 8, which is re-printed below for convenience. Once fuel providers gather raw materials, they must be processed and distributed. The next chapter describes and quantifies the costs of fuel processing and transportation.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Biomass	Coal	Oil	Gas	Net	
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Corn	$4.62	4.51	0	0.022	0.085	0.058	0.165	2.9

Table 8: Raw Feedstock Summary Table

3 Biomass Densification and Fuel Distribution

The previous chapter showed the relative benefits and drawbacks of different biomass fuel feedstocks. The energy densities for raw feedstocks are considerably less than fossil fuel energy densities, 75% less by mass and 90% less by bulk volume. The bulk volumetric energy densities vary too much by fuel, and are too low in many cases to be economically transported from the production to consumption sites. There are many methods available to convert these fuels in to more usable and dense forms, but these conversions are often expensive and energy inefficient. Some examples of biomass conversion processes include thermo-chemical, e.g. Fischer-Tropsch, and biological, e.g. fermentation.

This chapter reviews two low cost, high efficiency methods to increase biomass fuel energy density: pelletization and fast pyrolysis. The two resulting crude fuel forms, pellets and pyrolysis oil, are not useable for high-end applications such as motor vehicle fuels but are sufficient for space heating. The transportation infrastructure necessary to deliver the resulting fuels to the end consumer is also reviewed.

3.1 Dense Solid Bio-Fuels

The simplest method to increase biomass volumetric density is compressing the biomass into pellets. Compressing biomass fuels can increase average bio-fuel volumetric energy density and decrease its variability. Bio-fuel compression does not change the mass energy density. Besides increasing the volumetric energy density, compression also increases fuel uniformity, both in terms of size and moisture. Figure 9 shows the standard pellet qualities, according to the Pellet Fuels Institute, a non-profit association that serves the pellet industry in the United States.

Property	Value	Units
Density	> 641	kg/m^3
Length	< 38	mm
Diameter	6.3	mm
Fines	< 0.5%	Weight % passing through a 3.2mm screen
Chlorides	< 300	ppm
Ash Content		
– Premium Grade	< 1 %	Weight %
– Standard Grade	< 3%	Weight %

Figure 9: Pellet Fuel Properties and Picture [PFI, 2007]

One major drawback to compressing solid bio-fuels is their resulting solid form, which makes handling more difficult than the simple piping required for liquid and gaseous fuels. Solid fuel handling infrastructure is less developed than liquid and gaseous fuel infrastructure, especially in home and commercial heating. Some infrastructure can be leveraged from the agricultural industry, since it has a long history of handling small solids, such as grains.

Besides providing examples of infrastructure for pellets, grains can also be used to provide heating fuel. Corn provides a special case for dense solid bio-fuels. Corn kernels have inherently high volumetric energy density, very similar to pellets. Kernels provide the benefits of pellets without the added compression steps required by wood and switchgrass. The existing corn handling infrastructure also provides a model for pellet infrastructure development if pellet fuels become more common in the future.

3.1.1 Pellet Production

Pellet production began in earnest during the oil crises in 1973 and 1979 to offset high oil prices. The high oil prices at that time led to quick pellet-fuel adoption, but the later price decline eliminated most demand. The recent increases in heating prices have once again increased the demand for wood pellets, the most common and best developed solid bio-fuel. Today, most pellets are produced from waste wood chips and dust, such as sawdust from a lumber mill. This feedstock is very cheap and already dried and ground into small particles, thus minimizing costs of production. Other feedstocks, such as switchgrass, can be used to meet pellet demand if the solid bio-fuel heating rates continue to increase, though grass-pellet process development is less mature than wood pellet processing. This section reviews the basic steps and associated costs for producing bio-fuel pellets from waste wood and switchgrass, which include: feedstock drying (waste wood only), grinding, pelletizing, cooling, and storage. The following analysis uses cost estimates from Polagye [Polagye, 2005] and assumes a 300 ton per day (tpd) capacity, 10% discount rate, and 80% load factor, and 10 year equipment life. Electricity and raw biomass energy prices are consistent with previous definitions in this paper.

The pelleting process requires relatively dry feedstock, 10-15% moisture content by mass [Polagye, 2005, p55]. Raw wood chip moisture content is too high to be pelleted directly, thus it must be dried first. Drying units cost about \$2,200,000 in capital at the 300 $ton_{pellets}$/day processing scale, including suspension burners to use wood chips for process heat. Drying equipment amortized capital costs contribute \$4.07/$ton_{pellets}$ to net production costs.

Besides increasing capital costs, drying also consumes considerable energy.

Dryers consume 3.5 $GJ_{heat}/ton_{pellets}$. Currently most dryers consume natural gas for heating. If future solid bio-fuel adoption rates increase due to increasing costs of fossil fuels, this heat should be derived from bio-fuels, and eventually from bio-fuel combined heat and power (CHP) facilities. This analysis considers the medium term case of using raw biomass for heating. At a waste wood price of $\$3.20/GJ_{wood}$, the average cost of drying is $\$10.50/ton_{pellets}$. The rotary driers also consume electricity to run fans and agitators, which consume an additional 33.7 $kWh/ton_{pellets}$, adding $\$1.93/ton_{pellets}$ to the production costs.

Given the considerable costs associated with drying, it is worth noting that some feedstocks do not require drying, such as switchgrass. The standard switchgrass harvesting practice leaves the cut grass in the field to dry, leading to harvested moisture contents around 10-15%. This saves considerable money and energy when pelletizing switchgrass relative to wood.

After drying, the feedstock must be ground into small, uniform pieces. Grinding begins with pre-screening to remove debris that might harm the equipment, such as stones or metal. Grinding and pre-screening equipment costs $224,000 for 300 tpd capacity. This translates to $0.42/ton-pellets in capital cost. Grinding also consumes considerable amounts of energy, 127 $kWh/ton_{pellets}$ of electricity, which costs $\$7.28/ton_{pellets}$. Future grinders may be powered by bio-fuels, but those systems are currently too expensive and complex to be considered here.

Next, the dried and ground material must be compressed into bio-pellets. The pelleting process relies on the relatively low glass temperature of lignin. Lignin acts as the glue holding cellulose together in biomass. When heating softens the lignin, the ligno-cellulosic material can be easily molded. The pellet production system heats the feedstock while pressing the material through a die, forcing the cylindrical shape. The heated lignin is partially fluidized, allowing the material to flow through the die. When the cylinder is sufficiently long, a knife cuts the bio-pellet, determining its length.

Several types of pelleting machines are available today. The two basic forms of presses used by the pelleting machines are: rotary and piston. Rotary presses are more common and will be used for pricing and energy consumption rates. A rotary press, show in Figure 10, uses a roller to press the biomass through a cylindrical die that contains many holes. The roller rotates within the die, and at each pass over a hole in that die presses a small amount of biomass into it. This material builds up and pushes the compressed biomass out of the other end of the hole, to the die exterior, where it is cut off by the knife.

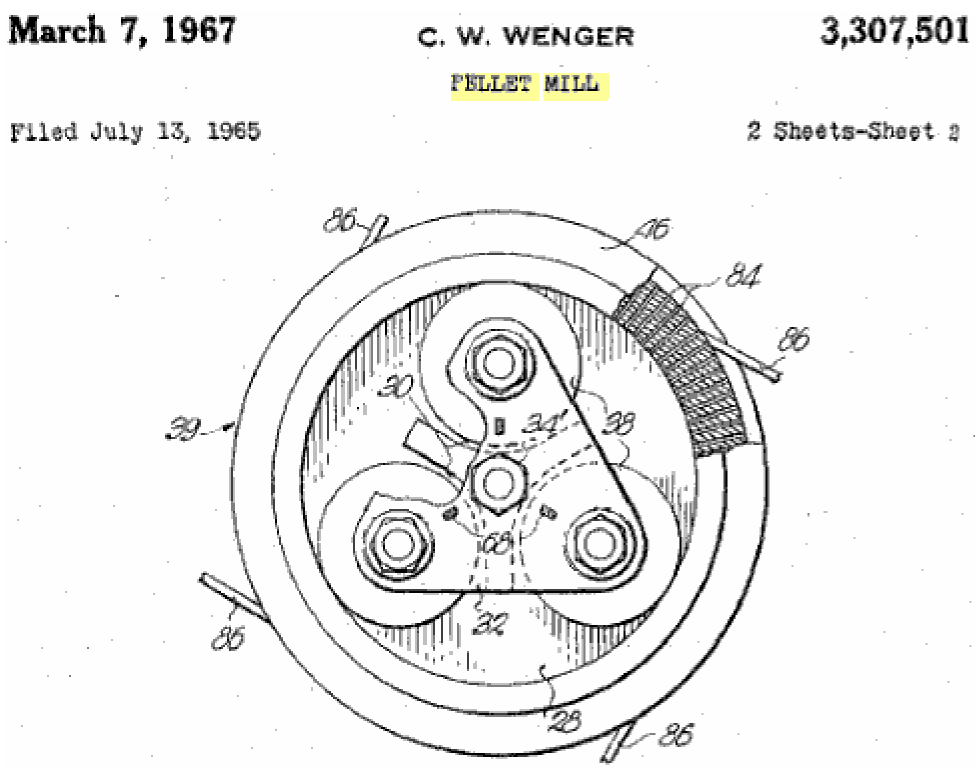


Figure 10: Image of a Rotary Pellet Press [Wenger, 1967]

An alternative to the rotary press is the piston press. Piston pelletization is inherently a batch process. The machine adds biomass to a cylinder and then uses a large piston or screw at one end to compress it within the cylinder. The pressure and heat eventually build up until the biomass flows out of the die at the other end of the cylinder. This approach has the potential of saving money and energy by using the high pressure state in the cylinder to press water out of a wet feedstock, avoiding drying costs. The benefits of water pressing have not proven to be economically viable.

After passing through the dies, bio-pellets must cool to increase the lignin rigidity, allowing the pellet to keeps its shape under stressed conditions. Cooling generally takes place by blowing ambient air over the pellets. After cooling, pellets are moved to a storage bin where they accumulate and await transportation.

The back-end production system, pelletizing, cooling, and storage, adds cost and energy consumption to bio-fuel production. The total back-end system costs $1,600,000 for 300 tpd capacity, which is the equivalent of $\$2.93/\text{ton}_{\text{pellets}}$. Operation and maintenance costs add another $\$15/\text{ton}_{\text{pellets}}$, including replacement dies and additives. Rotary pelletizers consume 114 kWh of electricity for each ton of pellets produced.

At the end of the process, the pellet volumetric energy density is 10 GJ/m^3, making pellets more manageable to transport than wood chips or raw switchgrass. The pellets are also more uniform than wood chips and switchgrass, making them more similar to grains, allowing the use of agricultural transportation infrastructure. The economic and energy costs associated with pellet production are shown in Table 10 and Table 11. The total cost of production for wood pellets is $3.63/GJ. Despite the lower energy density, switchgrass pellets are less expensive to produce, $3.30/GJ, since the switchgrass pelleting process avoids the expensive and energy intensive drying step. Switchgrass pellet production also consumes less energy than wood pellet production, having a net energy efficiency of 88%, relative to a 71% net energy efficiency for wood pellet production.

Item	Economic Costs ($/GJ)			Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
	Cap.	O&M	Net		Bio.	Coal	Oil	Gas	Net	
Production										
Wood Pellets	$0.37	$3.30	$3.67	0.77	0.175	0.082	0.005	0.030	0.292	2.7
Switchgrass Pellets	$0.20	$3.11	$3.30	3.30	0	0.085	0.005	0.031	0.121	2.6

Table 10: Economic and Energy Costs Associated with Pellet Production

Process	Capital ($/dtpd)	O&M ($/ton)	Heat Consumed (GJ/odt)	Electricity Consumed (kWh/odt)	Total Cost ($/dt)	Wood Pellets ($/GJ)	Switchgrass Pellets ($/GJ)
Drying	**$ 7,283**	**$ -**	**3.5**	**33.7**	**$ 16.50**	**$ 0.83**	
Rotary Drum Dryer	$ 5,000		3.5	33.7			
Suspension Burner	$ 2,283						
Grinding	**$ 747**	**$ -**	**0**	**127**	**$ 7.69**	**$ 0.38**	**$ 0.45**
Grinder Capital Cost	$ 405						
Metal Separation	$ 45						
Ground Conveyence	$ 298						
Hammer Mill Power				127			
Pellet Production	**$ 5,245**	**$ 15.00**	**0**	**114**	**$ 24.46**	**$ 1.22**	**$ 1.44**
Live Bottom Bin	$ 769						
Pellet Mill	$ 3,528						
Pellet Cooler	$ 516						
Pellet Shaker	$ 79						
Storage	$ 133						
Fork Lift	$ 102						
Mis. Conveyors	$ 118						
Die and Roller Replacements		$ 5.00					
Additives		$ 10.00					
Labor		$ 10.00			**$ 10.00**	**$ 0.50**	**$ 0.59**
Other		$ 14.00			**$ 14.00**	**$ 0.70**	**$ 0.82**
Total	$ 13,275	$ 39	3.5	274.7	$ 73	$ 3.63	$ 3.30
Wood Chip Fuel Cost ($/GJ)	$ 3.00		**Capactity**	300	dtpd	**Discount Rate**	10%
Electricity Cost ($/kWh)	$ 0.06		**Life of Equip.**	10	Years	**Load Factor**	80%

Table 11: Economic and Energy Cost Breakdown for Wood and Switchgrass Pelletization [Polagye, 2005]

3.1.2 Corn and Pellet Transportation

After pressing switchgrass and wood chips into pellets, they must move to the end consumer. Producers accumulate large pellet quantities in a few locations, and must move those pellets to distributors. Corn kernels are also accumulated in large quantities at grain elevators. At this stage, all three fuel types are treated identically for transportation calculation purposes. One exception to this rule is the correction for different energy densities. Delivered corn at 15% moisture and switchgrass pellets at 10% moisture have mass energy densities 10% and 15% lower than wood pellets at 10% moisture, respectively. All future calculations will be based on wood pellets and then adjusted for corn and switchgrass pellets in the summary table.

The solid bio-fuel transportation infrastructure currently consists of two basic stages: delivery to the distributor and delivery from the distributor to end consumers. There is currently an additional stage, packaging at the distributor. Packaging is left out of this analysis since alternatives to bagging must be adopted to enable easier consumer use, which is required for more widespread adoption. Pneumatic bulk solids delivery systems are already in place in some regions such as Germany, making bulk pellet delivery easier and bagged pellets obsolete.

Based upon corn delivery estimates from Shappouri et al., we assume 40 miles traveled in a class 8 truck to collection terminals, followed by 400 miles of rail or barge transportation [Shappouri, 2002, p8]. To simplify the analysis, this paper assumes that rail transportation is used since its energy intensity is higher, and thus is the more conservative assumption. Total energy consumed during bulk transportation is thus 0.024 $GJ_{oil}/GJ_{pellets}$. The price of this transportation is approximately \$1.20/$GJ_{pellets}$

assuming costs of \$0.02 per ton-mile for rail and \$0.27 per ton-mile for trucking [BTS, 2006, Table 3-17].

Solid bio-fuel distribution consumes another 0.038 $GJ_{oil}/GJ_{pellets}$, increasing consumer costs by \$2.22/$GJ_{pellets}$. These values assume that delivery trucks hold an average of six tons of bio-fuels while making one ton deliveries to the consumer, with twenty miles of travel between deliveries [GGG, 2005, p2]. These assumptions result in a delivery cost of \$35/ton. Table 12 shows the total economic and energy costs associated with solid bio-fuel transportation.

	Energy (GJ-oil/GJ-fuel)	Cost (2005$/GJ-fuel)
Wood Pellets	0.024	$1.20
Switchgrass Pellets	0.028	$1.41
Corn	0.027	$1.35

Table 12: Transportation Energy and Economic Costs for Solid Bio-fuels

3.1.3 Solid Bio-Fuel Summary

Providing solid bio-fuel to end consumers requires significant effort. For wood and switchgrass, the raw material must first be converted to pellet form. Pellets and corn must then be transported to distributors, and finally distributed to the end consumers. The total economic and energy costs for solid bio-fuels, from cultivation to transport, are shown in Table 13, as well as the net CO_2 emissions. This analysis shows corn as the least expensive and lowest carbon emission fuel, as delivered to end consumers. The corn ranking is counter to the initial findings, since corn had the highest energy intensity for production. The fact that corn does not require the costly pelletization step enables this higher fuel system efficiency and lower fuel system cost.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Bio.	Coal	Oil	Gas	Net	
Raw Feedstock								
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Corn	$4.62	4.51	0	0.022	0.085	0.058	0.165	2.9
Production								
Wood Pellets	$3.67	0.77	0.175	0.082	0.005	0.030	0.292	2.7
Switchgrass Pellets	$3.30	3.30	0	0.085	0.005	0.031	0.121	2.6
Transportation								
Wood Pellets	$1.20	0.77	0	0	0.024	0	0.024	0.4
Switchgrass Pellets	$1.41	3.30	0	0	0.028	0	0.028	0.5
Corn	$1.35	4.51	0	0	0.027	0	0.027	0.5
Total Fuel Costs								
Wood Pellets	**$8.07**	0.77	0.175	0.082	0.075	0.030	0.362	**4.0**
Switchgrass Pellets	**$8.22**	3.30	0.000	0.085	0.101	0.031	0.217	**4.4**
Corn	**$5.98**	4.51	0.000	0.022	0.112	0.058	0.192	**3.4**

Table 13: Economic, Energy, and Carbon Summary Table for Solid Bio-Fuels

Now that the cost associated with solid bio-fuel production and delivery are accounted for, the next section reviews the corresponding costs associated with bio-oil production.

3.2 Bio-Oil

Bio-oil is another densification alternative that is highly efficient and inexpensive. Bio-oil refers to the condensable oils that emerge from biomass when it is heated rapidly, a process known as pyrolysis, and then cooled. Bio-oil is distinctly different from both crude oil and bio-diesel: it consists of a wide array of organic molecules including organic acids, alcohols, aldehydes, esters, and ketones.

The following section provides greater detail about what bio-oil is, how it is made, and special concerns regarding its delivery and storage. As with previous sections, it describes the economic and energy costs associated with each step.

3.2.1 Bio-Oil Fuel Properties

Bio-oil is a complex, dynamic, and potentially hazardous mixture of chemicals. The condensable pyrolysis oils that make up bio-oil are a combination of mostly aromatic hydrocarbons. The actual composition of bio-oil depends heavily upon the base feedstock used and processing conditions [Diebold, 2000, p11]. Table 14 provides examples of compositions created by various feedstock and processing conditions. The chemicals in bio-oil react with each other, dynamically maintaining an apparent equilibrium. The high organic acid content leads to a low pH, 2.3 to 3, which causes storage and handling issues that will be discussed later in section 3.2.3 [Diebold, 2000, p6].

The mass energy density of delivered bio-oil is similar to pellets, 16.4 $GJ/ton_{bio\text{-}oil}$ relative to 18 $GJ/ton_{wood\text{-}pellets}$ and 15.3 $GJ/ton_{switchgrass\text{-}pellets}$. The high oxygen content in the bio-oil molecules reduces the energy density on a dry basis relative to crude oil derivatives, as Table 15 shows. The mass energy density for delivered bio-oil is also lower due to the large moisture content. Bio-oil contains approximately 27% water, which is formed during the high temperature pyrolysis process. Note that Table 14 and Table 15 show various water quantity levels. The value of 27% water is based upon the full scale facility processes assumed in this economic analysis based upon a study by Bridgwater [Bridgwater, 2002, p202].

Representative Condensable Vapors

Weight % Yield of Dry Biomass

	University of Waterloo – Fluidized Bed			NREL – Vortex
Component	**Poplar (504°C)**	**Maple (508°C)**	**Spruce (500°C)**	**Oak (~500°C)**
Acetic Acid	5.4	5.8	3.9	5.0
Formic Acid	3.1	6.4	7.2	3.3
Hydroxyacetaldehyde	10.0	7.6	7.7	4.3
Glyoxal	2.2	1.8	2.5	3.0
Methylglyoxal	*not found*	0.65	*not found*	*not found*
Formaldehyde	*not found*	1.2	*not found*	2.2
Acetol	1.4	1.2	1.2	1.8
Ethylene Glycol	1.1	0.6	0.9	*not found*
Levoglucosan	3.0	2.8	4.0	3.8
1,6-anhydroglucofuranose	2.4	*not found*	*not found*	*not found*
Fructose	1.3	1.5	2.3	*not found*
Xylose	*not found*	*not found*	*not found*	0.9
Glucose	0.4	0.6	1.0	*not found*
Cellobiosan	1.3	1.6	2.5	*not found*
Oligosaccharides	0.7	*not found*	*not found*	*not found*
Pyrolytic Lignin	16.2	20.9	20.6	24.9
Other Carbohydrates	11.9	17.1	12.9	5.8
Water	12.2	9.8	11.6	12.4

Table 14: Example Bio-Oil Compositions. Source: Polagye, 2005

Comparison of pyrolysis liquid and conventional fuel oil characteristics

		Pyrolysis liquid	Diesel	Heavy fuel oil
Density	kg/m^3 at 15°C	1220	854	963
Typical composition	%C	48.5	86.3	86.1
	%H	6.4	12.8	11.8
	%O	42.5	–	–
	%S	–	0.9	2.1
Viscosity	cSt at 50°C	13	2.5	351
Flash point	°C	66	70	100
Pour point	°C	−27	−20	21
Ash	%wt	0.13	<0.01	0.03
Sulphur	%wt	0	0.15	2.5
Water	%wt	20.5	0.1	0.1
LHV	MJ/kg	17.5	42.9	40.7
Acidity	pH	3	–	–

Table 15: Bio-oil Properties Relative to Petrochemicals [Bridgwater, 2002, p186]

Rapidly heating biomass converts most of the biomass to condensable pyrolysis oils, though not all. The remaining biomass is in the form of char or non-condensable gases, such as CO, H_2, and CH_4. The char component causes a problem with bio-oil stability since it generally stays with the bio-oil and acts as a catalyst, increasing the aging rate. The aging rate of bio-oil is an issue that will be discussed later in this section. Char may be separated while the pyrolytic oils are in vapor phase, though it is generally done in the liquid phase to expedite oil cooling. Upon separation, the char may be used as a fuel source. The non-condensable gases pass through the condensation chamber where most of the bio-oil is liquefied. Although these gases are not available as bio-oil, they are not completely lost with regard to energy conversion efficiency since they can be recycled into the reaction chamber and burned to provide process heat.

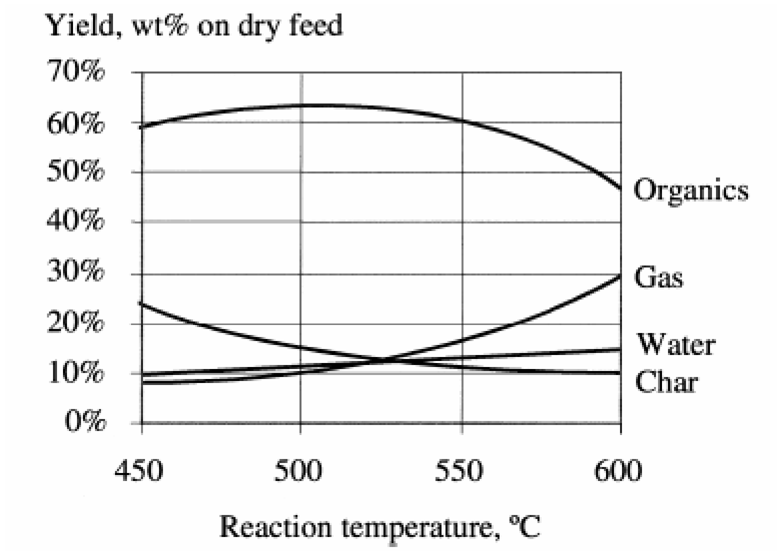
The dynamic nature of bio-oil chemical reactions causes its composition to change over time. These changes lead to increased viscosity and eventually phase separation into two immiscible phases, a process referred to as aging. The reactions that take place create long, cross-linked hydrocarbons and volatile hydrocarbons. Phase separation occurs as the polarity differences between longer hydrocarbons and organic acids increases. Aging is one of the primary concerns in bio-oil use, making low temperature storage critical to slow the effects [Diebold, 2000, p4]. Besides low temperature storage, there are three primary approaches to reducing aging rates: methanol blending, hydrodeoxygenation, and antioxidant addition.

Methanol slows the aging rate of bio-oil and reduces its viscosity, allowing longer storage times before an unacceptable viscosity is reached. Methanol blending decreases viscosity more than what is expected by dilution alone. It also improves aging characteristics by changing the reaction dynamics of the chemical mixture to prefer the formation of lighter, non-volatile products. This combination of decreased viscosity and reduced polymerization reactions reduces aging significantly. [Diebold, 2000, pp 32-34].

Mild bio-oil hydrogenation offers another mode to slow the aging process. Laboratory tests show successful aging rate decreases through hydrogenation, but at the cost of higher initial viscosity [Diebold, 2000, p34]. Antioxidant addition offers another approach to achieve more stable, slower aging bio-oil by disabling the free radicals present in the chemical mixture. Small amounts of hydroquinone, 0.10 to 0.25 wt%, are used to stabilize acrolein and acetic acid for storage.

3.2.2 Bio-Oil Processing

The key to bio-oil processing is to rapidly heat biomass, and then cool the resulting gasses. Biomass heating rates are critical to bio-oil conversion yields, with faster heating rates leading to improved bio-oil yield. Heating rates are affected by: feedstock moisture, feedstock particle size, and processing temperatures. Moisture in the biomass slows the heating process due to the large amount of thermal energy required to vaporize the water. Small feedstock particle sizes are critical to increase the ratio of thermally exposed surface area to thermal mass. Elevated temperatures increase the thermal gradient between the biomass particle exterior and the cooler particle interior, forcing a faster heat transfer rate. Elevated temperatures also degrade bio-oil conversion since the condensable oils quickly degrade into incondensable gases as the temperature increases. Figure 11 shows the relationship between reaction temperature and pyrolysis reaction yields. As the temperature increases from 450 C the heating rate increases, leading to a higher yield of organics (bio-oil). Above 500 C the effect of excess bio-oil transformation to gas begins to dominate the curve, driving the bio-oil yield down. Bio-oil reactors can provide conversion efficiencies as high as 80% by weight [Bridgwater, 1999, p1482]; though 70% conversion efficiency is assumed for this analysis. The following analysis considers the impacts of processing costs on the economics and efficiencies associated with bio-oil processing.



Typical yields of organic liquid, reaction water, gas and char from fast pyrolysis of wood, wt% on dry feed basis.

Figure 11: Fast Pyrolysis Yield as a Function of Reactor Temperature [Bridgwater, 1999, p1480]

Bio-oil processing begins with two fundamental pre-treatments: drying and grinding. Drying reduces the energy consumed during rapid heating and enables faster heating rates. The drying process for bio-oil pretreatment is similar to drying for pelletization, so the cost and efficiency values from section 3.1.1 are used. In the case of switchgrass, drying takes place in the field before harvest, so the drying costs are not present in switchgrass based bio-oil production. Grinding reduces the mass to surface area ratio, enabling more rapid heating. Grinding costs are again taken from section 3.1.1.

Different techniques and bio-oil production reactor types can provide the rapid heating rates required to drive the fast pyrolysis reaction. These reactor types include: fluidized beds, ablative, and rotating cone. Fundamentally, reactors provide rapid heating by bringing small amounts of dry biomass in contact with a large thermal mass that is at an elevated temperature. Fluidized beds insert biomass particles into a massive bed of small, rapidly mixing, hot particles. Ablative reactors use larger biomass particles, but introduce only one surface of the particle to a hot, thermally massive surface that is moving past the particle. The movement keeps the area contacting the particle from excessive cooling and removes char formations to continuously provide new, cool biomass to the hot interacting surface. Rotating cone reactors inject small biomass particles into a rotating cone, which forces the particles across the surface of the heated cone, providing consistently hot surfaces to drive the pyrolysis reaction. Schematics of all three designs are shown in Figure 12 below.

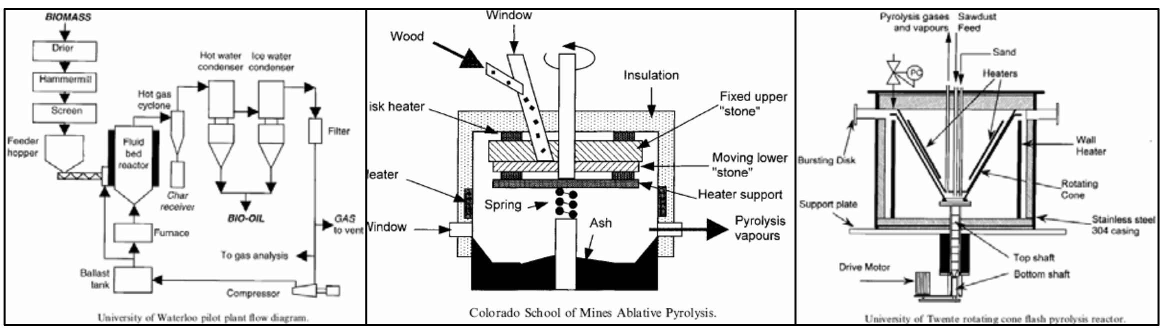


Figure 12: Pyrolysis Reactor Types: Fluidized Bed, Ablative, and Cyclone (from left to right) [Bridgwater, 2000, pp 57, 23, 54]

Bridgwater surveyed a series of reactor designs to develop an economic model for pyrolysis reactors. This survey showed the following relationships between production rates and cost [Bridgwater, 2000, pp 203-204]. The costs are associated with whichever reactor is the most effective for the plant size considered, not one specific reactor type. Values have been adjusted to 2005 U.S. dollars from 2000 €.

$$\text{Pyrolysis Plant Capital Cost} = 42.8*(Q/\eta)^{0.6194}*1000$$

$$\text{Storage Capital Cost} = 125*(Q)^{0.4045}$$

$$\text{Labor (number of people during operation)} = 1.04*Q^{0.475}$$

Q = the total plant capacity in dry-ton/hour feedstock input

η = bio-oil mass conversion efficiency

Pyrolysis reactors also consume energy during operation. The processing heat is provided by char and incondensable gas combustion. Bridgwater estimates that pyrolysis processing demands 40 kWh of power, likely electricity, for each dry-ton of [Bridgwater, 2000, p204].

Converting raw feedstock into bio-oil requires drying, grinding, and a pyrolysis reaction. Drying and grinding steps are very similar to those required by pelleting processes. Pyrolysis reactions require less energy input than pelletization, but is has lower mass conversion efficiency. The total processing costs at the 300 dtpd (dry ton per day) output capacity are $1.88/GJ for processing wood into bio-oil and $0.98/GJ for switchgrass without drying. Table 16 also shows that the fossil fuel consumption is relatively low for production. The elevated biomass fuel consumption is due to the lost material during conversion. The detailed production cost calculations are shown in Table 17.

Item	Economic Costs ($/GJ)			Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
	Cap.	O&M	Net		Bio.	Coal	Oil	Gas	Net	
Production										
Wood Bio-Oil	$0.31	$2.94	$3.24	0.55	0.651	0.076	0.005	0.028	0.759	2.9
Switchgrass Bio-Oil	$0.06	$3.06	$3.12	2.31	0.429	0.075	0.004	0.027	0.535	2.8

Table 16: Pyrolysis Oil Production Cost Summary

Process	Capital ($/dtpd)	O&M ($/odt)	Heat Consumed (GJ/odt)	Electricity Consumed (kWh/odt)	Total Cost ($/dt-oil)	Wood Bio-Oil ($/GJ)	Switchgrass Bio-Oil ($/GJ)
Drying	**$ 7,283**	**$ -**	**3.5**	**33.7**	**$ 24.57**	**$ 1.09**	
Rotary Drum Dryer	$ 5,000		3.5	33.7			
Suspension Burner	$ 2,283						
Grinding	**$ 747**	**$ -**	**0**	**127**	**$ 10.99**	**$ 0.49**	**$ 0.57**
Grinder Capital Cost	$ 405						
Metal Separation	$ 45						
Ground Conveyence	$ 298						
Hammer Mill Power				127			
Bio-Oil Production	**$ 683**	**$ 2.76**		**40**	**$ 7.76**	**$ 0.35**	**$ 0.41**
Pyrolysis Reactor	$ 682						
Storage	$ 1						
Labor		$ 2.76					
Total	**$ 8,713**	**$ 3**	**3.5**	**200.7**	**$ 43**	**$ 1.93**	**$ 0.98**

Wood Chip Fuel Cost ($/GJ)	**$3.20**	**Capactity**	**300**	**dtpd**		**Discount Rate**	**10%**
Electricity Cost ($/kWh)	**$0.06**	**Equipment Life**	**10**	**Years**		**Load Factor**	**80%**
Labor Cost ($/hr)	**$10.00**	**Conv. Eff. (dry wt)**	**70%**	**Product Moisture**	**27%**	**Feed Moisture**	**10%**

** Note that the costs shown do not include the cost of any feedstock material, including the material lost during conversion

Table 17: Cost and Energy Consumption Calculation for Producing Bio-Oil from Wood and Switchgrass [Bridgwater, 2000]

3.2.3 Bio-Oil Transportation

After bio-oil is produced, it must be distributed to consumers. This analysis assumes that the distribution pathway is similar to that of pellets. The mass energy density differences between the fuel types change the costs slightly, as Table 18 shows.

Item	Economic Costs ($/GJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
		Bio.	Coal	Oil	Gas	Net	
Transportation							
Wood Pellets	$1.20	0	0	0.024	0	0.024	0.4
Switchgrass Pellets	$1.41	0	0	0.028	0	0.028	0.5
Corn	$1.35	0	0	0.027	0	0.027	0.5
Bio-Oil	$1.32	0	0	0.026	0	0.026	0.5

Table 18: Transportation Costs for Wood and Switchgrass Bio-Oil Relative to Pellets and Corn

Though the delivery costs are similar, the fuel delivery trucks would vary considerably between the dry and wet fuels. This calculation implicitly assumes that the capital and operation costs for the trucking systems are similar per unit mass carried. There is a price premium paid for the solid transport systems due to their lower volumetric energy density, 10 GJ/m^3 for solids vs. 20 GJ/m^2 for bio-oil. There is also a price premium paid for bio-oil transport systems since they must hold highly acidic fluid. This analysis implicitly assumes that capital cost premiums for the both fuel transport systems are equal.

3.2.4 Bio-Oil Summary

Bio-oil can provide a low cost and high efficiency bio-fuel for low-grade purposes though its storage issues make it undesirable for residential energy use. The total cost of production and delivery is $7.79/GJ to $8.12/GJ, with carbon emissions of only 4.7 $kg_{Carbon}/GJ_{bio\text{-}oil}$ to 5.1 $kg_{Carbon}/GJ_{bio\text{-}oil}$. Table 19 shows the cost breakdown for bio-oil production.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Bio.	Coal	Oil	Gas	Net	
Raw Feedstock								
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Production								
Wood Bio-Oil	$3.24	0.55	0.651	0.076	0.005	0.028	0.759	2.9
Switchgrass Bio-Oil	$3.12	2.31	0.429	0.075	0.004	0.027	0.535	2.8
Transportation								
Bio-Oil	$1.32		0	0	0.026	0	0.026	0.5
Total Fuel Costs								
Wood Bio-Oil	**$7.76**	0.55	0.651	0.076	0.096	0.028	0.851	**4.6**
Switchgrass Bio-Oil	**$8.56**	2.31	0.429	0.075	0.128	0.027	0.658	**4.6**

Table 19: Bio-Oil Production Cost Breakdown

Bio-oil storage has three basic problems: aging, low pH, and harmful constituent chemicals. One method to address all three issues is chemical separation, or distillation. Distillation provides a static equilibrium of constituent chemicals, thus eliminating aging. Distillation can also remove the organic acids and other hazardous compounds. This distillation process is costly, however, and creates a stream of distinct chemicals, listed in Table 14. If the costly separation does take place, it is more cost profitable to sell the separated constituents as premium feedstocks to the chemical production industry than to sell them as inexpensive fuel.

The risks associated with bio-oil storage make it unlikely for widespread adoption. Although future technologies may alleviate aging, pH, and hazardous chemical content associated with bio-oil in a low cost manner, it is currently too dangerous to expect consumers store bio-oil in their homes and businesses today. Due to the current limitations, heating with bio-oil is not considered further in this paper, even though the economics and energy efficiency appear favorable.

3.3 Biomass Densification and Fuel Distribution Summary

The costs of producing all of the low-grade bio-fuels considered are similar. The total cost of production for low grade bio-fuels ranges from \$6/GJ to \$9/GJ, with the carbon emissions ranging from 3.8 kg_C/GJ_{fuel} to 4.9 kg_C/GJ_{fuel}, as is shown in Table 20. Although the feedstock costs are greatest for corn, the energy saved by eliminating the processing steps necessary for pelletization make it the least costly in both economic and energy terms. Bio-oil and pellets have very similar costs, but bio-oil chemical properties make it unsuitable for residential use at this time. If future research finds a low-cost method of reducing bio-oil hazards it may prove to be a more beneficial fuel since it is a liquid fuel.

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Bio.	Coal	Oil	Gas	Net	
Raw Feedstock								
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Corn	$4.62	4.51	0	0.022	0.085	0.058	0.165	2.9
Production								
Wood Pellets	$3.67	0.77	0.175	0.082	0.005	0.030	0.292	2.7
Switchgrass Pellets	$3.30	3.30	0	0.085	0.005	0.031	0.121	2.6
Wood Bio-Oil	$3.24	0.55	0.651	0.076	0.005	0.028	0.759	2.9
Switchgrass Bio-Oil	$3.12	2.31	0.429	0.075	0.004	0.027	0.535	2.8
Transportation								
Wood Pellets	$1.20	0.77	0	0	0.024	0	0.024	0.4
Switchgrass Pellets	$1.41	3.30	0	0	0.028	0	0.028	0.5
Corn	$1.35	4.51	0	0	0.027	0	0.027	0.5
Bio-Oil	$1.32		0	0	0.026	0	0.026	0.5
Total Fuel Costs								
Wood Pellets	**$8.07**	0.77	0.175	0.082	0.075	0.030	0.362	**4.0**
Switchgrass Pellets	**$8.22**	3.30	0.000	0.085	0.101	0.031	0.217	**4.4**
Corn	**$5.98**	4.51	0.000	0.022	0.112	0.058	0.192	**3.4**
Wood Bio-Oil	**$7.76**	0.55	0.651	0.076	0.096	0.028	0.851	**4.6**
Switchgrass Bio-Oil	**$8.56**	2.31	0.429	0.075	0.128	0.027	0.658	**4.6**

Table 20: Total Production Cost Summary for Low Grade Bio-Fuels

Providing low-cost and highly efficient fuels is not sufficient to make a significant change in energy consumption. These fuels must be matched with technologies that can effectively utilize them. Section 4 reviews the handling and combustion technologies necessary to make these fuels viable for residential and commercial heating.

4 Heating with Solid Bio-Fuels

Chapter four considers the differences between existing oil heating systems and solid bio-fuel heating systems. Cost and usability differences between oil and solid bio-fuel are important since consumers are unlikely to adopt technologies that cost more or require significantly more effort to operate. The system differences between solid bio-fuel and heating oil considered span from fuel delivery to waste disposal, and include extensive review of biomass combustion. Furnace integration with existing duct work or hot water piping remains basically unchanged, and so is not considered here.

4.1 Fuel Storage and Handling

Solid bio-fuel handling and storage consists of two basic stages: transferring fuel from the delivery truck to long term storage, and transferring fuel to the combustion chamber. When a stage in the solid bio-fuel heating system has multiple technology alternatives, the current technology is described first, then the preferred mode or modes for future development. All conveyance and storage solutions must minimize physical damage to the solids, keep them dry, and prevent pest infestation, e.g. rodents or insects.

Solid bio-fuels delivery currently takes place in bulk or bagged form. Bagged delivery involves trucks bringing a number of 18 kg bags, generally 55 bags for a one ton delivery. The delivery person and/or the consumer manually move the bags into the designated storage area. Current storage areas are usually garages or basements. Most consumers are unlikely to adopt solid bio-fuel heating if it requires the physically intensive activity of manually moving heavy bags. Bagged fuel delivery also requires an extra bagging step, which consumes more energy and materials while adding to the cost of fuel production. Although fuel bagging is not the preferred approach, it is currently the dominant delivery method in the United States.

Bulk solid bio-fuel delivery resolves many of the problems associated with bagged delivery. Bulk delivery involves a truck filled with loose pellets or corn conveying part of its load to an enclosed storage area or bin. The fuel is conveyed from the truck to the bin by either an auger system or pneumatic solids conveyor. Distributors in the United States and Europe have used both methods. The agricultural industry also uses both systems for grain handling; thus the technology is well developed and can be leveraged for solid bio-fuel delivery.

Grain augers are the older of the two technologies, and simpler to operate. Augers are rigid and require close proximity between the fuel truck and storage bin. This proximity requirement means that the either the storage bin location is limited to areas near vehicle access points, e.g. road or driveway, or that the delivery vehicle must move onto unprepared surfaces, e.g. the consumer's lawn. Both options are undesirable, leading to a preference for pneumatic fuel handling.

Pneumatic solid bio-fuel transport systems enable greater flexibility than auger systems. Pneumatic systems create an air-stream with sufficient velocity to carry solids with it, similar to vacuum cleaners. This entrained flow requires fairly uniform solids, in terms of size, shape, and mass, to be most effective. The delivery person can then move the tubing that carries the solid entrained air-flow around corners to the fuel storage destination. The tubing has a minimum allowable radius of curvature, but those limits are less restrictive than the rigid auger system.

Pneumatic conveyance systems must extract solids from the air-stream and place them into the storage bin. Separation can take place by simply blowing the air/solid stream into a large bin with an air outlet, similar to blown insulation, or by passing the air/solid stream through a cyclone separator. Blowing the solids into the bin requires a pressurized delivery truck to provide the pressure differential necessary for airflow development. Pressurized storage tanks are more expensive than unpressurized tanks, thus they increase the costs for bulk delivery.

The delivery truck storage tank may be left at ambient pressure if the pneumatic delivery exhaust is at sub-atmospheric pressure. Fans and compressors can be used to provide the necessary suction if the exhaust is free of solid bio-fuel. Cyclone separators can be used to efficiently pull solid bio-fuel from the airflow. Cyclone and air suction systems can be part of the delivery truck, leaving the storage bin as simple as possible. These systems are already used in the agricultural industry at scales necessary for residential and commercial solid bio-fuel delivery. For example, the “SeedVac” bulk seed conveyor can pneumatically move 180 kg/minute of corn kernels through a flexible hose that is operated by a single person, as shown in Figure 13 below [Christianson, 2007]. The “SeedVac” can deliver as much fuel in five and a half minutes as one pallet of 55 18-kg bags.

Figure 13: One Person Handling the "SeedVac" to Transport Grain at Over 180 kg/min Through a Flexible Hose [Christianson, 2007]

Both bulk delivery systems require one large storage bin to hold the solid bio-fuel in long term storage. This bulk storage can either be part of the furnace, or a separate exterior bin. Indoor bulk storage has the benefit of requiring only one more fuel handling stage before combustion, but takes up valuable interior space. The low solid bio-fuel volumetric energy density makes that interior space consumption larger than oil storage.

Outdoor storage is another option for solid bio-fuels, which is unavailable for heating oil. Heating oil is stored indoors to ensure that the temperature remains sufficiently high. Low temperatures cause heating oil to gel, restricting or stopping fuel flow to the furnace. Solids, when sufficiently dry, do not have this problem, and thus can be stored outside during winter. Exterior storage enables much larger bins without sacrificing indoor area. Some consumers may prefer a larger bin, which would enable less frequent fillings. Exterior bins do require an extra handling step, however, since the fuel must move to a small interior short-term storage bin. This conveyance may take place by either pneumatics or an auger depending upon the location logistics. The small interior short-term storage would be filled periodically from the exterior bin throughout the day.

Once the fuel is in the furnace system, an auger meters the fuel into the combustion chamber. The auger pulls the fuel either from the interior long-term storage bin attached to the furnace or the short-term storage bin, in the case of exterior long-term storage. The auger system must be able to provide the right amount of material to the combustion chamber to ensure proper air/fuel mixtures. The auger system must also provide protection from back burning, which occurs when the combustion chamber flame travels up the conveyance system to the storage bin.

4.2 Solid Bio-Fuel Furnace Technology

Once the fuel is in the combustion chamber, two modes of combustion are available: single stage and dual stage. Single stage combustion occurs when all of the combustion air is presented to all of the available solid fuel, similar to wood in a fireplace or camp-fire. This mode of combustion produces high pollutant levels such as nitrogen oxides (NO_x), volatile organic compounds (VOCs), and condensable organic compounds (tars). The high pollutant emissions make single stage combustion undesirable; it is mentioned only as a reference. Dual stage combustion, the preferred mode, provides more beneficial performance than single stage combustion.

Dual stage combustion takes place in two parts: primary partial combustion then secondary complete combustion with excess air. The primary combustion chamber introduces just enough air to the pellets or corn to cause pyrolysis and partial char oxidation, producing a large quantity of combustible gases. The secondary combustion chamber mixes those combustible gases with the secondary air stream, providing a more uniform flame that causes almost all of the carbon to react and form carbon dioxide. The added air in the secondary combustion chamber is greater than the stoichiometric combustion requirement to keep temperatures below 1100 C, the temperature at which NO_X formation rates increase significantly. Completing combustion in the gaseous phase also provides more uniform combustion, which reduces the pollutant emissions associated with solid-air mixtures found in single stage combustion.

The emissions performance improvements of dual stage combustion with wood pellets are best shown through emissions comparisons. Figure 14 shows the emissions measured from single stage wood log combustion, dual stage wood log combustion, and dual stage wood pellet combustion. Dual stage wood pellet combustion provides the lowest emissions by far in CO, CH_4, VOC, and PAH (Polycyclic Aromatic Hydrocarbons). The particulate and NO_X emissions are reduced by less significant margins.

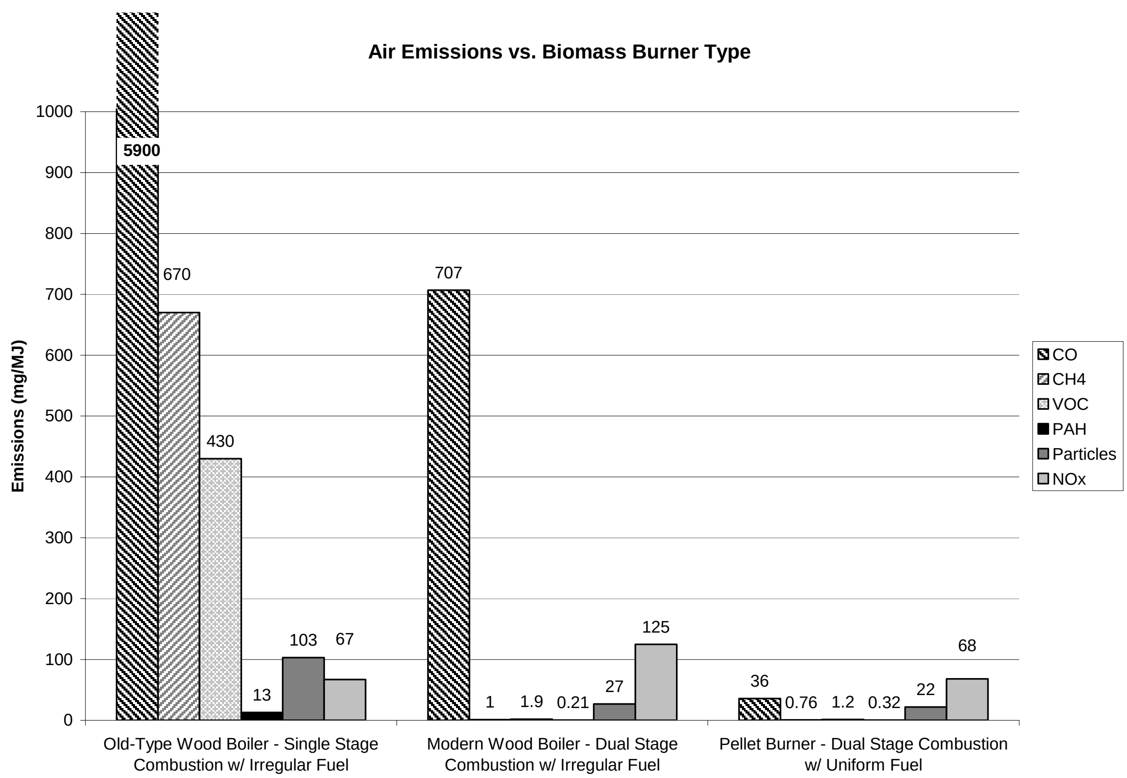


Figure 14: Combustion Emissions for Various Burner Types in Home Heaters [Johansson, 2004, p4188]

Clearly pellet burners provide superior emissions relative to older wood combustion, but their performance relative to oil furnaces is more relevant. Figure 15 shows pellet burner pollutant emissions relative to oil burners. CO emissions are an order of magnitude greater in the pellet burner, while particle and NO_X emissions are roughly double. Potential actions to reduce emissions are considered below for: products of incomplete combustion (PIC), NO_X, and particles.

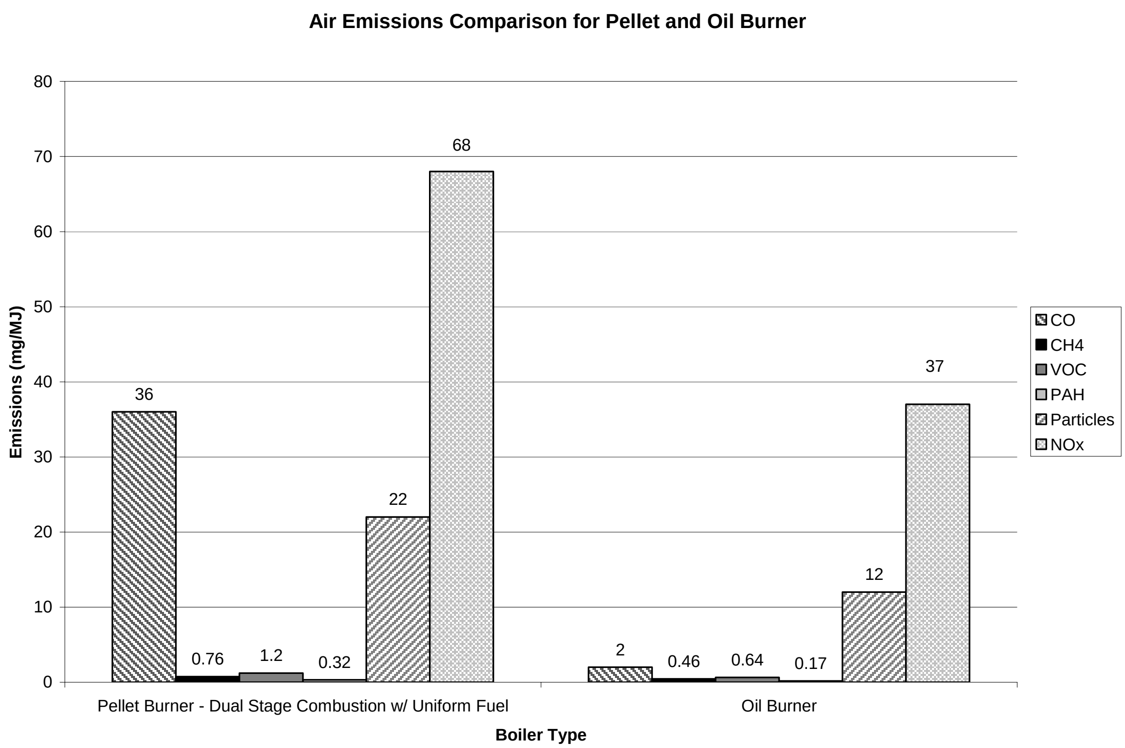


Figure 15: Combustion Emissions Comparison between Wood Pellet and Oil Burners [Johansson, 2004, p4188]

Most of the emissions shown are products of incomplete combustion. These emissions include CO, CH_4, VOC, and PAH. Two viable options to reduce these emissions are: changing combustion technology or catalytic flue gas treatments. A third possible option is increasing the maximum combustion temperature, but this would increase NO_X emissions. Combustion technology changes that increase combustion residence time reduce PIC emissions. Increasing the combustion residence time requires a larger combustion chamber and would thus increase the furnace costs. Alternatively, catalysts may increase the reaction rates at lower temperatures, thus allowing a smaller combustion chamber, but requiring the additional cost of a catalytic converter.

Pellet burners have two sources of nitrogen for NO_X production: the fuel and air. Nitrogen is present in the fuel in the form of proteins and other nitrogen-containing molecules. It is thus difficult to further decrease NO_X emissions, since lower temperature combustion to reduce NO_X would increase the PIC and would only address air-derived NO_X formation. NO_X-reducing solutions such as catalytic conversion are costly and may decrease the economic viability of solid bio-fuel furnace adoption. Platinum is the preferred catalyst for this function, which is both expensive and sensitive to fouling from other chemicals in the exhaust stream.

Elevated particulate levels have more options for abatement than PIC or NO_X. There are several flue gas treatment options available for particle emissions reduction. Some examples are simple physical filtration and electrostatic precipitators. High efficiency furnace designs inherently reduce particulate emissions. Water condensation in the heat exchangers captures some of airborne particles and pulls them from the exhaust. Figure 16 shows the impact of several gas cleanup technologies on exhaust particle emissions. Note that particulate emissions may be reduced by 50% to 99.9%, depending upon the technology chosen.

Main flue gas cleaning equipment.

Technology	Process description
Cyclone/ Multi-cyclone	Cleaning, thereby extracting dust particles from the flue gas by centrifugal action taking place in vertical tubes.
Baghouse filter	The flue gas passes through fine-meshed/pored bags that trap the suspended solid particles. Bags are periodically cleaned from the surface by pressurised air. Operation temperature: up to 850°C, but normally between 160 and 220°C. Operation pressure : up to 50 bars, but normally atmospheric pressure.
ESP	Electrostatic precipitator: The flue gas passes through an electric field, and the particles precipitate on electrodes. Dry and Wet ESP can be distinguished. Dry ESP: Operation temperature: up to 480°C, but normally <250°C. Operation pressure : up to 20 bars, but normally atmospheric pressure. Wet ESP : in combination with flue gas condensation unit. Higher precipitation efficiency than dry ESP, but sludge/water separation necessary. Usually operates between 45 and 55°C at atmospheric pressure.
Flue gas scrubber	The flue gas passes through a shower so that the particles are trapped/caught in the water.
Flue gas condensation	The flue gas is cooled to below the dew point, and the particles are absorbed/trapped by the dew.

Dust precipitation efficiency.

		Cyclone – multi-cyclone	Flue gas condensation	Dry ESP	Wet ESP	Baghouse filter
Cut size	μm	~ 5		~ 0.1	~ 0.1	~ 0.1
Separation efficiency	%	85 - 95	50 - 90	95 – 99.9	95 – 99.9	99 – 99.9
Max. operation temperature	°C	1300	< dew point	480	At dew point	850
Max. operation pressure	Bar	100	atmospheric	20	20	50
Investment		Low	High	High	High	High
Operation costs		Moderate	Low	Low	Low	Moderate

Conclusion regarding fly ash precipitation technology with respect to the emission limit.

Emission limit	Best applicable techniques
< 150 mg/Nm3	Multi cyclone
< 50 mg/Nm3	Flue gas condensation units, dry ESP
< 20 mg/Nm3	Dry or wet ESP
< 10 mg/Nm3	Baghouse filter, wet ESP

Figure 16: Particle Reduction Technologies for Solid Biomass Furnaces and Boilers [Pastre, 2002, p73]

In addition to the elevated air pollutant emissions, solid bio-fuel furnaces and boilers are also less efficient than heating oil burners. High water content and irregular fuel qualities reduce the combustion and heat extraction efficiency. The annual fuel utilization efficiency (AFUE) for pellet stoves varies from 70% to 83%. This analysis assumes 75% AFUE, near the average published efficiency, for future calculations. Solid bio-fuel furnace and boiler efficiencies are low relative to oil based systems, which have AFUE ratings from 85% to 95% for condensing oil furnaces. The analysis in this paper assumes oil furnaces have 85% AFUE since that is the value for furnaces used in economic comparisons in this paper [Braaten, 1999, p19].

4.3 Ash Management

In addition to air pollutants, solid bio-fuel combustion also has non-combustible waste that must be managed. Incombustible ash presents a furnace design problem unique to solid bio-fuels. Heating oil produces little to no ash since the incombustibles are cleaned from the fuel before distribution. Solid bio-fuel pre-treatments cannot strip the incombustibles from the fuel without conversion into gaseous or liquid form. The furnace design must therefore be robust to ash and enable its removal.

Solid bio-fuel furnaces must manage two basic ash types: fly-ash and bottom-ash. Bottom-ash is the incombustible material that the air-stream does not carry, while fly-ash is the incombustible material that moves with the air-stream. Both fly-ash and bottom-ash may either be slagging or dry. Slagging ash, or slag, is fused incombustible material that coagulates and hardens upon cooling, often on furnace surfaces. Dry ash is the incombustible material that does not have a melting component, and so remains powdery, fine, and mobile.

Slag forms when the combustion temperature is greater than the fusing temperature of the material. The material slag temperature depends upon the mixture of incombustibles in the ash and their fusing temperatures. For example, high concentrations of Silicon and Potassium lead to reduced slag temperatures. Slag occurs when those incombustibles fuse then harden as they cool. Slag causes “clinkers” in old coal fired heaters. Modern biomass furnaces either avoid slagging or include slag management systems to address the problem.

To avoid slag, furnaces must maintain low combustion temperatures and use fuels with sufficiently high slag temperatures. Solid bio-fuels slag temperatures vary by feedstock. Wood pellets are the commonly available pellet type currently, and usually have high slag temperatures. As pellet demand increases, the variety of source materials will also increase, potentially including feedstock materials with inherently low slag temperatures. To avoid slag issues, the maximum burner temperature should be measured and clearly displayed in solid bio-fuel burner systems, along with the heating system's slag management capabilities. The solid bio-fuels should also carry fuel slag temperature certification and labeling, enabling the consumer or distributor to match acceptable fuel types with the furnace. Fuel additives such as limestone can raise the slag temperature to enable processors to meet high temperature standards even with low grade fuels [Ohman, 2004, p1376].

Slag management systems are more complex than non-slagging systems. The combustion chamber can contain most of the bottom ash slag. The slag management system in the burner then removes the slag while it is still in its molten state, or cools the slag and removes the solidified substance. Though these slag management systems work well for slagging bottom ash, slagging fly ash may foul downstream heat exchanger surfaces. The solidified fly ash slag reduces heat transfer rates in the heat exchanger and can be very difficult to remove. Fly ash is more difficult to remove from the furnace since it becomes distributed over a greater area. The furnace design must either remove the fly ash from the air-stream before reaching the heat exchangers or there must be mechanisms to clean the heat exchangers. Most current fly ash slag management systems clean the heat exchanger surfaces. Some burners require consumers to manually clean the surfaces. This is problematic because furnaces must be self-cleaning to enable widespread adoption. Automatic heat exchanger surface cleaners are already found in some European pellet furnace designs [Fiedler, 2003, p6].

After the furnace gathers the fly and bottom ash, the solid bio-fuel system must remove it. This removal is usually done manually. Some current solid bio-fuel heating systems include pneumatic removal by the fuel distributor during fuel deliveries, making waste removal invisible to the consumer and allowing the high mineral ash to return to the distributor for redistribution as a fertilizer, if desired.

The minerals present in ash are important plant fertilizers. The minerals consumed by the plants producing the biomass are locked into the ash, thus they are necessary for plant growth and should be distributed back to that purpose. Ideally, the ash would travel backward through the supply chain to fertilize the fields that produced the solid bio-fuel. A more realistic solution is selling the ash as a natural fertilizer. Although this may not return the minerals to their origin, it would displace mineral consumption for fertilization to offset the fertilization taking place on the solid bio-fuel feedstock production fields.

4.4 Solid Bio-Fuel Heating Summary

Chapter four reviews some challenges posed by solid bio-fuel storage, handling, and consumption. Solid bio-fuel storage is the least technically challenging problem, since the primary drawback is the large volume required. The logistics of storage are relatively simple since the storage system must only keep the fuel pest-free and dry. These simple requirements contrast with heating oil’s need for complete sealing to avoid leakage and location in a warm place to avoid gelling.

Solid bio-fuel handling is more problematic. Solids are inherently more difficult to move into a heating system combustion chamber than liquids. Pneumatic systems offer more robust and flexible fuel handling than the current manual mode and can be leveraged from existing knowledge in the agriculture industry. These solid handling technologies are also needed for user-friendly ash removal.

The combustion chamber changes significantly from oil to solid bio-fuel based heating. The best solid bio-fuel combustion systems use a dual stage burner design, which is more difficult than for oil burners but required for clean solid bio-fuel combustion. Pollutant emissions from dual-stage biomass combustion are greater than those for oil combustion, but much lower than for single-stage biomass combustion. Regulations on solid bio-fuel boilers and furnaces should set acceptable NO_X, CO, PAH, and particulate emission levels based upon air quality needs, regulating by emissions instead of combustion technology.

Ash maintenance is the most challenging aspect of solid bio-fuel heating. The heating system must clean the combustion chamber and exhaust surfaces to maintain proper combustion and heat transfer characteristics. Automated cleaning is highly recommended to enable widespread adoption, but this requires improvements upon the more common manual cleaning systems. Two basic types of ash handling systems are slag-free combustion and slag management. Slag free systems require high-slag temperature fuels. As feedstock diversity increases, low slag temperature fuels will become more common, requiring fuel standards that include slag temperature certification and eventually heating systems that include automated slag management.

Finally, solid bio-fuel furnaces and boilers are less efficient than high-efficiency oil furnaces and boilers. Solid bio-fuel heating systems must consume more fuel than oil systems to make up the difference. For example, one gallon of heating oil has a higher heating value of 0.149 GJ_{fuel} which provides 0.127 GJ_{heat}. For corn to provide this same heat, the heating system must burn 0.169 GJ_{fuel} of corn, or 0.411 bushels. The total effect of efficiency and fuel prices on heating costs is shown in Table 21. Heating oil prices are based on the 2005 United States average heating oil price to the consumer [EIA, 2006B, p34].

Item	Economic Costs ($/GJ)	Quantity Available (EJ)	Energy (GJ-in/GJ-out)					Carbon Emissions (kg-C / GJ)
			Bio.	Coal	Oil	Gas	Net	
Raw Feedstock								
Forest Residue	$3.20	0.90	0	0	0.046	0	0.046	0.9
Switchgrass	$3.50	3.30	0	0	0.068	0	0.068	1.3
Corn	$4.62	4.51	0	0.022	0.085	0.058	0.165	2.9
Heating Oil	$13.29	0.86	0	0	1.000	0	1.000	18.9
Production								
Wood Pellets	$3.67	0.77	0.175	0.082	0.005	0.030	0.292	2.7
Switchgrass Pellets	$3.30	3.30	0	0.085	0.005	0.031	0.121	2.6
Transportation								
Wood Pellets	$1.20	0.77	0	0	0.024	0	0.024	0.4
Switchgrass Pellets	$1.41	3.30	0	0	0.028	0	0.028	0.5
Corn	$1.35	4.51	0	0	0.027	0	0.027	0.5
Heating Oil	$0.47	2.31	0	0	0.009	0	0.009	0.2
Total Fuel Costs								
Wood Pellets	**$8.07**	0.77	0.175	0.082	0.075	0.030	0.362	**4.0**
Switchgrass Pellets	**$8.22**	3.30	0.000	0.085	0.101	0.031	0.217	**4.4**
Corn	**$5.98**	4.51	0.000	0.022	0.112	0.058	0.192	**3.4**
Heating Oil	**$13.76**	0.86	0.000	0.000	1.009	0.000	1.009	**19.1**
Heating Efficiency								
Solid Bio-fuel	75%							
Heating Oil	85%							
Total Heating Cost								
Wood Pellets	**$10.76**	0.57	0.233	0.110	0.100	0.040	0.482	**5.3**
Switchgrass Pellets	**$10.96**	2.48	0.000	0.113	0.135	0.041	0.289	**5.9**
Corn	**$7.97**	3.38	0.000	0.029	0.149	0.077	0.256	**4.6**
Heating Oil	**$16.19**	0.73	0.000	0.000	1.187	0.000	1.187	**22.4**

Table 21: Economic and Carbon emission Costs of Heating by Fuel Type

The cost of heating with for corn and wood-pellets is much lower than for heating oil, based upon 2005 average prices, even when accounting for efficiency differences. Heating with the most expensive solid bio-fuel, switchgrass pellets, costs 32% less than heating with oil. Burning corn for heat provides the greatest heating cost benefit at 2005 average prices, saving 51% relative to heating oil.

Regarding scalability to a national scale, waste wood alone can satisfy most of the heating oil replacement needs, which the least available of all of the fuels. The total heating energy currently available from wood and corn is over five times the total commercial and residential demand for heat from heating oil. Potential switchgrass production alone could provide over three times the current oil-heat demand. Finally, solid bio-fuel life-cycle CO_2 emissions are 74-80% less than the heating oil emissions that they displace. Completely replacing heating oil with solid bio-fuels would save 13 million metric tons of Carbon emissions annually, roughly 0.7% of the 2005 United States emissions. [EIA, 2006G]

5 Prospects for Large Scale Low-Grade Bio-Fuel Deployment

The previous chapters reviewed the costs associated with solid bio-fuel production and use, as well as technologies that could make solid bio-fuel furnace and boiler ownership as simple to operate as oil-based heat for consumers. Chapter five considers the larger impacts of solid bio-fuel adoption. Section 5.1 assesses the economic risks and benefits associated with solid bio-fuel heating relative to oil-heat. Section 5.2 quantifies the heating oil market size to establish the impact of full scale solid bio-fuel adoption on energy security, global climate change, and other environmental externalities. Finally, section 5.3 reviews the existing policies that impact solid bio-fuel heating adoption.

5.1 Economic Analysis

Consumers have an economic incentive to purchase solid bio-fuel heaters if the cost savings of consuming solid bio-fuel instead of oil is greater than the additional up-front price paid for the more advanced solid bio-fuel heating system. The actual difference in cost between a solid bio-fuel heating system and oil heating system is unknown since solid bio-fuel systems are relatively new and thus robust technology and cost comparisons are unavailable. The premium paid for solid bio-fuel heating systems relative to oil-heat systems ranges from $1,000 to $12,000, though U.S. market sampling suggests that the current price premium is closer to $2,500 for 100 MJ/hour furnaces.

The following analysis considers the amount that a consumer should be willing to pay for the ability to burn solid bio-fuels instead of heating oil. The specific condition considered is when a consumer must purchase a new furnace or boiler, either for new construction or to replace an old malfunctioning unit. Although this condition provides the lowest hurdle for cost effectiveness, it inherently limits new consumer adoption rates since existing functional furnaces and boilers will not be replaced. A cost effective solution requires the net present value of fuel savings to be greater than the price premium paid for the solid bio-fuel furnace, relative to an equivalent oil furnace. For example, a $4,000 solid bio-fuel furnace that has the same capabilities as a $2,500 oil furnace would have a $1,500 price premium, thus it must provide a net present fuel savings greater than or equal to $1,500 to be cost effective. The analysis also calculates the value of flex-fuel heating systems with the ability to use oil or solid bio-fuel, depending upon which fuel is cheaper. The major cost of oil and solid bio-fuel system flexibility is in the fuel storage systems. The marginal cost of adding fuel flexibility to a bio-heat system is lower for consumers that already have oil storage, since the oil storage system is a significant part of flex-fuel heating system cost. This analysis requires some basic assumptions: lifetime of equipment, discount rate, and fuel cost differential.

The fifteen year lifetime assumption provides a conservative depreciation estimate for capital costs. Heating systems regularly last longer than fifteen years, though the effect of lifetime on economic calculations becomes much smaller after fifteen to twenty years, so the impact of assuming a longer life is relatively small.

The analysis also assumes a 10% discount rate. This value is considerably larger than the interest rate on most home improvement loans, providing some added economic incentive for action. Though the home improvement loan rate may be more applicable, a 10% discount rate provides a conservative estimate for investment.

The cost differential between fuel types is more difficult to estimate since they change over time. This analysis considers two approaches to fuel price changes: static and dynamic. Static pricing considers the effect of fuel price differences that are fixed over time. Static pricing is more intuitive and provides a good understanding of the impact of pricing changes on the economic viability of the capital investment. The dynamic model accounts for trends in annual fuel pricing behavior, including volatility. Dynamic modeling results also quantify the value of fuel flexibility in furnace designs.

5.1.1 Static Economic Modeling

A net present value analysis allows us to compare the cost effectiveness of bio-heat and oil-heat with static fuel prices. The results from this net present value analysis at different annual heat consumption rates are shown in Figure 17. The net present value of savings, or net present savings, is the value that consumers should be willing to pay above the price of an oil furnace or boiler. Thus a net present value of $3,000 suggests that if an oil furnace were $2,000, the consumer could pay up to $5,000, $3,000 more than the oil furnace cost, and break even or save money. Fuel savings from using corn instead of oil at 2005 prices was $8.22/$GJ_{heat}$, translating to a price premium of $3,750 for consumers demanding 60 GJ of heat, the 2001 national average for oil heat consumers [EIA, 2001]. If oil and corn prices stayed constant at 2005 values, a consumer should be willing to pay up to $3,750 more than the cost of an oil furnace for a solid bio-fuel furnace.

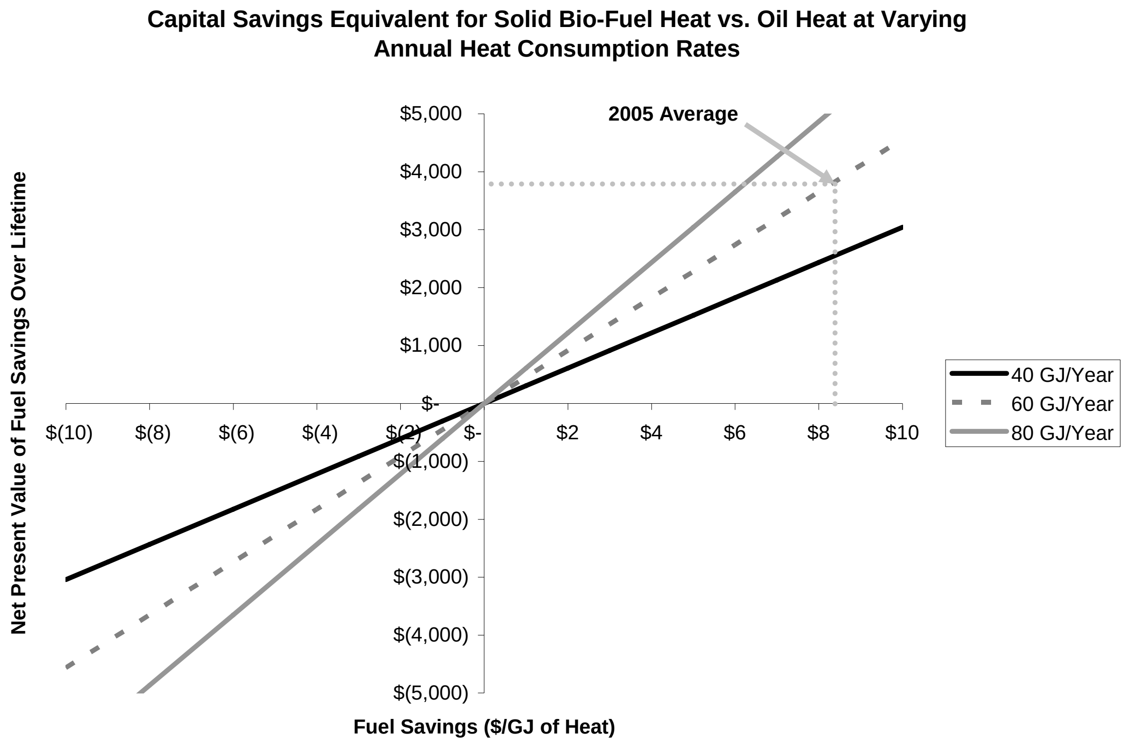


Figure 17: Net Present Value for Heating Fuel Savings at Varying Annual Heat Consumption Rates

Figure 17 also shows that the amount of heat consumed has a positive impact on the net present savings. Consumers that demand more heat should be willing to pay more for the solid bio-fuel furnace. Institutional and commercial heating oil consumers thus benefit more from fuel savings than residential consumers, and should be willing to pay a larger premium for the upgrade that enables lower cost fuels. Large consumers often pay much closer to the wholesale heating oil price, however, which is less than the residential delivered heating oil prices that were used in the previous calculation. In 2005, the average heating oil price paid by commercial and institutional consumers was $1.80/gallon, or $14.23/$GJ_{Heat}$ [EIA, 2006C]. Figure 18 shows the impact of fuel heat savings on several levels of commercial demand. The commercial heating demand levels shown are the average heat consumed by: warehouses (the least consumer); the national average for commercial oil consumption; and educational buildings (the greatest consumer). If corn were used instead of oil at the 2005 prices, the cost savings would be $6.26/GJ$_{Heat}$, a net present value of $12,600 for warehouses, $25,000 for average building consumption, and $91,700 for educational buildings.

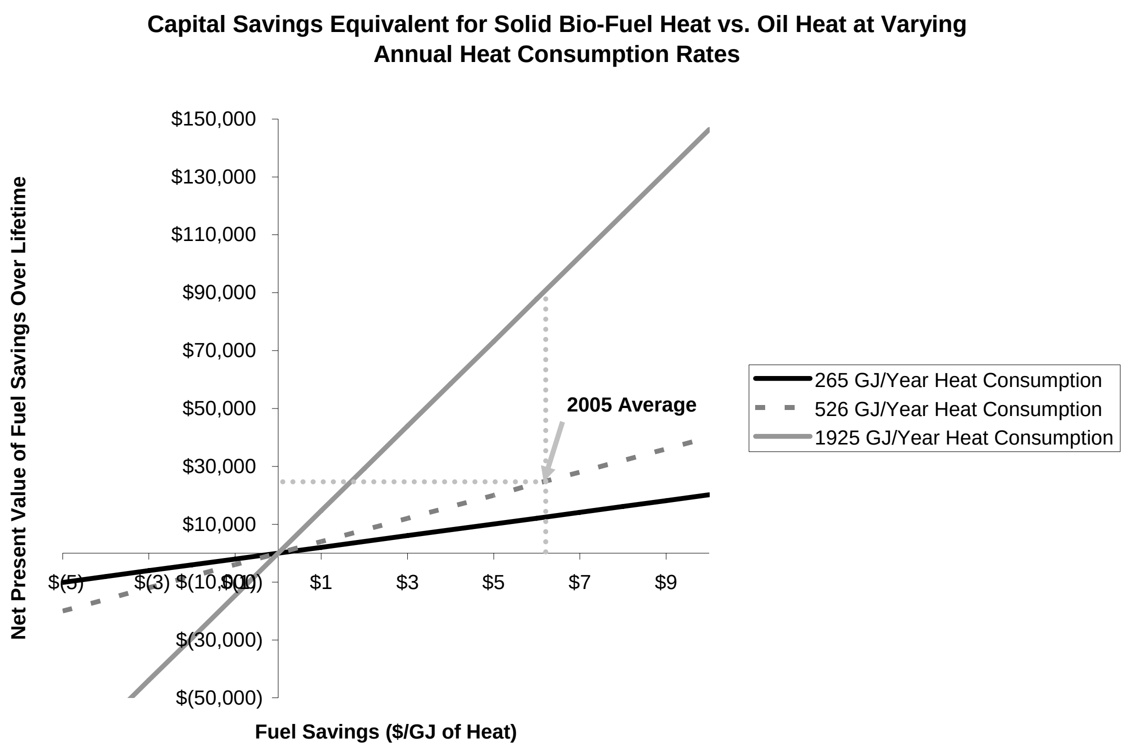


Figure 18: Fuel Savings Net Present Value for Warehouse (265 GJ$_{heat}$/year), Average (526 GJ$_{heat}$/Year), and Educational (1925 GJ$_{heat}$/Year) buildings

5.1.2 Dynamic Economic Modeling – Extrapolation from 2005 Prices

Although static net present savings calculations help illustrate the basic relationship between fuel prices and net present savings, the cost of fuel realistically changes over time. A more complex model considers the effects of fuel price trends and volatility. This analysis uses the binomial lattice approach to project future prices. Appendix A provides a brief description of how binomial lattice price extrapolations are calculated.

The first step for developing future prediction is establishing a trend in growth and volatility. Both corn and heating oil prices offer readily available histories, complete with average annual price paid for the commodity. The price histories are taken from the United States Energy Information Agency [EIA, 2006C] and the U.S. Department of Agriculture National Agricultural Statistics Service [USDA, 2007]. In the case of oil, the pricing includes fuel delivery costs. For corn, the data is the average price paid to the producers. This analysis assumes that the previously calculated delivery premium of \$1.80/GJ_{heat} is constant and added to the variable cost of corn.

Prices from the last 20 years provided the historical trends used for extrapolation. The volatility of residential oil heat, assuming 85% conversion efficiency, was 18% with a 2.7% average annual growth rate. Corn-heat price volatility was 12% with a near zero annual price increase rate between 1985 and 2005, assuming 75% heat conversion efficiency. Robust price histories for wood pellets are unavailable. This analysis assumes that the price pressures for pellets would be similar to corn, thus the growth rate and volatility are assumed to be 0% and 12%, respectively.

Future fuel prices used in this analysis were extrapolated using binomial random motion, explained in Appendix A. The extrapolations were calculated using Microsoft Excel™ in a Monte Carlo simulation. Though binomial lattice extrapolation does not intelligently extrapolate commodity prices, it is more robust than assuming no changes and lends itself well to Monte-Carlo simulations. The extrapolation is sensitive to starting point conditions, so several different starting points for pricing are assumed, including: actual 2005 average prices, historical trend expected price in 2005, and historical trend pricing without the option of burning corn. For each scenario, the simulation is run 10,000 times to quantify potential pricing variations.

The first simulation assumes that prices varied randomly from their 2005 average prices. In 2005 corn-heat would have saved an average of $\$8.22/GJ_{heat}$ relative to oil heating. The average net present savings was \$6,170, with a standard deviation of \$3,530. The likelihood of corn furnaces producing a net present loss was 0.7%; this net present loss assumes that no price premium was paid for the corn furnace. Assuming that the bio-heat furnace cost \$2,500 more than a comparable oil furnace, the probability of a net present loss increases to 13%. Figure 19 shows the probability distribution function of net present savings from heating with corn, pellets, or a flexible fuel design that can use either solid bio-fuels or oil. The average added value of fuel flexibility was only \$330 since the projected fuel prices rarely warranted a switch from burning corn to burning pellets as fuel. The value of adding the option to heat with oil was nearly zero since the oil prices were rarely extrapolated to be below solid bio-fuel prices.

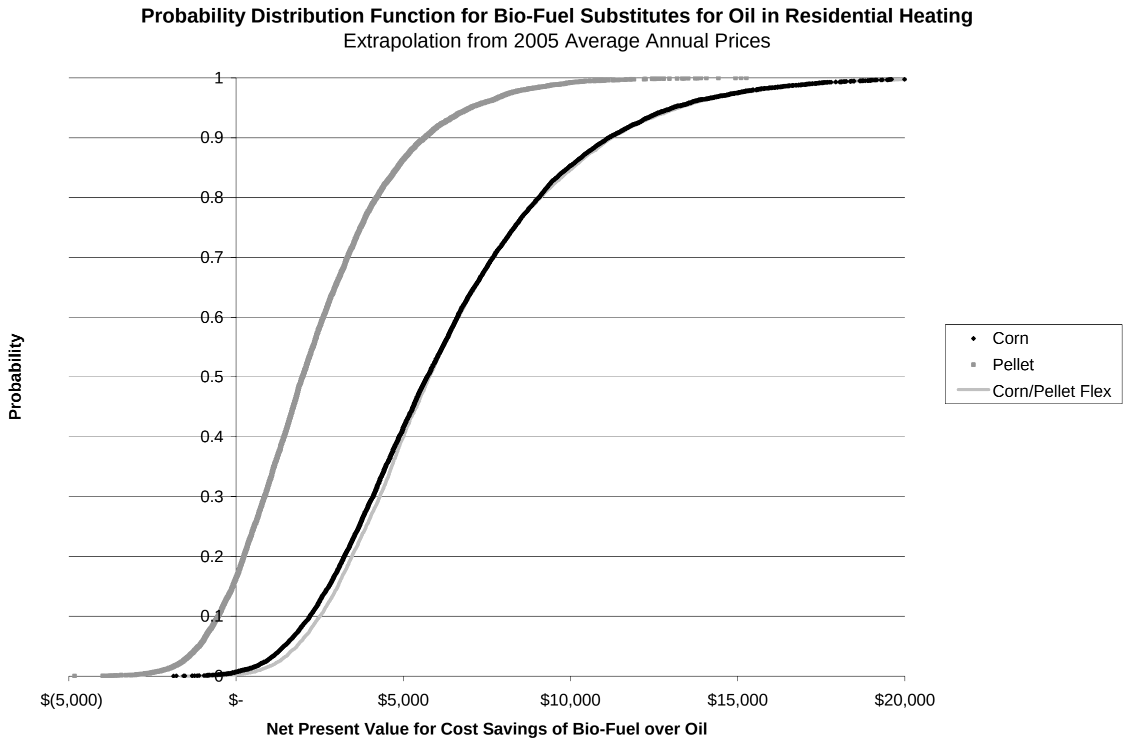


Figure 19: Probability Distribution Function for Residential Furnace Net Present Savings from Bio-Fuel Consumption Relative to Oil, Extrapolated from 2005 Average Fuel Prices

Next, the simulation calculated the expected savings for commercial heaters using the same approach. In this case, the prices of oil, corn, and pellets were much closer, making the savings per unit energy much less. The quantity of fuel consumed by commercial users was much greater, however, making the net present savings magnitudes larger. Assuming the average consumption of 526 GJ_{heat}/year, the net present savings from using a corn burner instead of oil was $43,400 with a standard deviation of $27,800. The average value for corn/pellet fuel flexibility was $2,120, with no value of oil burning flexibility.

5.1.3 Dynamic Economic Modeling – Conservative Price Extrapolation

High oil prices favor solid bio-fuel heating scenarios. Although oil prices are currently high, history has shown that they can quickly fall. Figure 20 shows the price of crude oil in the last 20 years with an exponential curve fit to the data [EIA, 2007]. Given the average historical price and growth rate, the expected crude oil price in 2005 was $37/barrel instead of the actual price of $57/barrel. Using a similar curve fitting method for heating oil the "expected", or conservative, price of oil heat and corn heat in 2005 was $\$10.75/GJ_{heat}$ and $\$8.80/GJ_{heat}$, respectively. At this conservative condition, the average net present savings of heating with solid bio-fuels was $2,660 if either pellets or corn could be used, with a $2,380 standard deviation. The probability of a negative net present savings was 11%. Corn was still the dominant solid bio-fuel in the scenarios from the "expected" condition, thus the value of adding fuel flexibility was only $351 for pellets and $180 for pellets and oil.

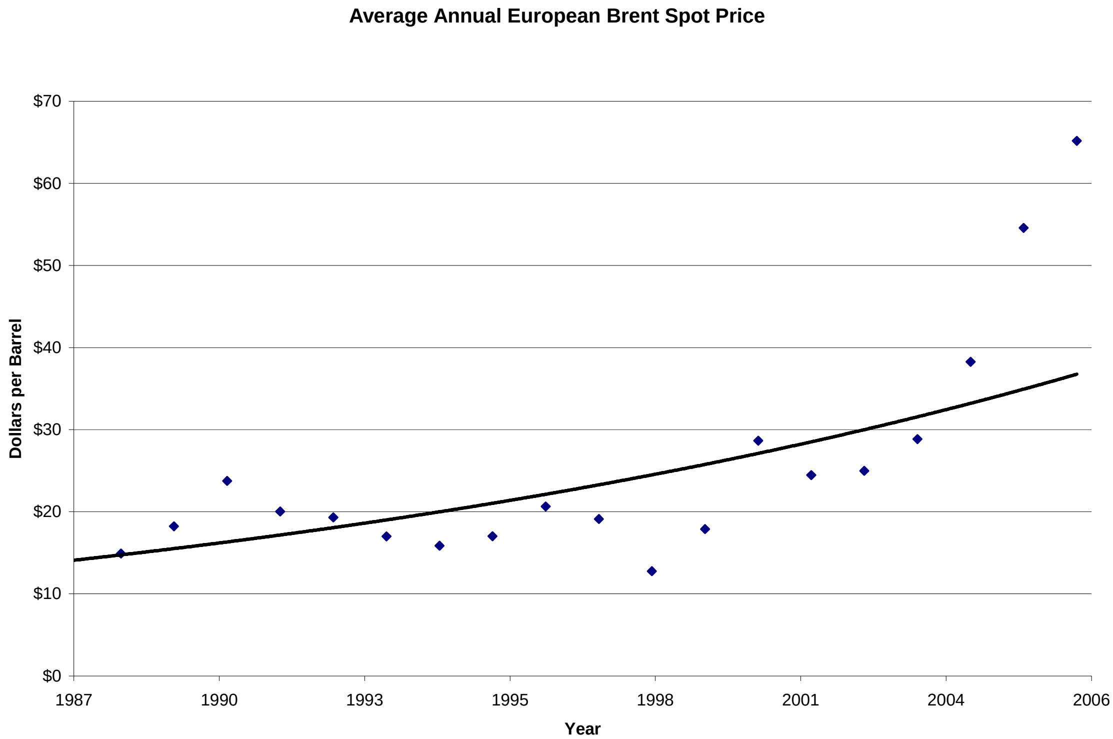


Figure 20: Average Annual Spot Price for European Brent with Exponential Trend Line [EIA, 2007]

Recent corn-ethanol regulation changes have increased the demand for corn, creating a corn price shock from a 2005 average of $1.90/bushel to over $4/bushel in 2007. At $4/bushel, corn heat prices increased to over $14/GJ$_{heat}$, making pellets more favorable. Without the option of using inexpensive corn for combustion, the expected net present savings for solid bio-fuel heat relative to oil heat was $1,340 with a $2,620 standard deviation. Under the conservative scenario, if a consumer pays a $1,340 premium for a bio-fuel heating furnace they have an equal chance of saving or losing money. Figure 21 shows the probability distribution functions for net present savings under the conservative pricing case. In this case, the added value of fuel flexibility was much greater, since the fuel prices were much closer to each other. Adding the ability to use oil in the solid bio-fuel furnace increased its net present savings by $560.

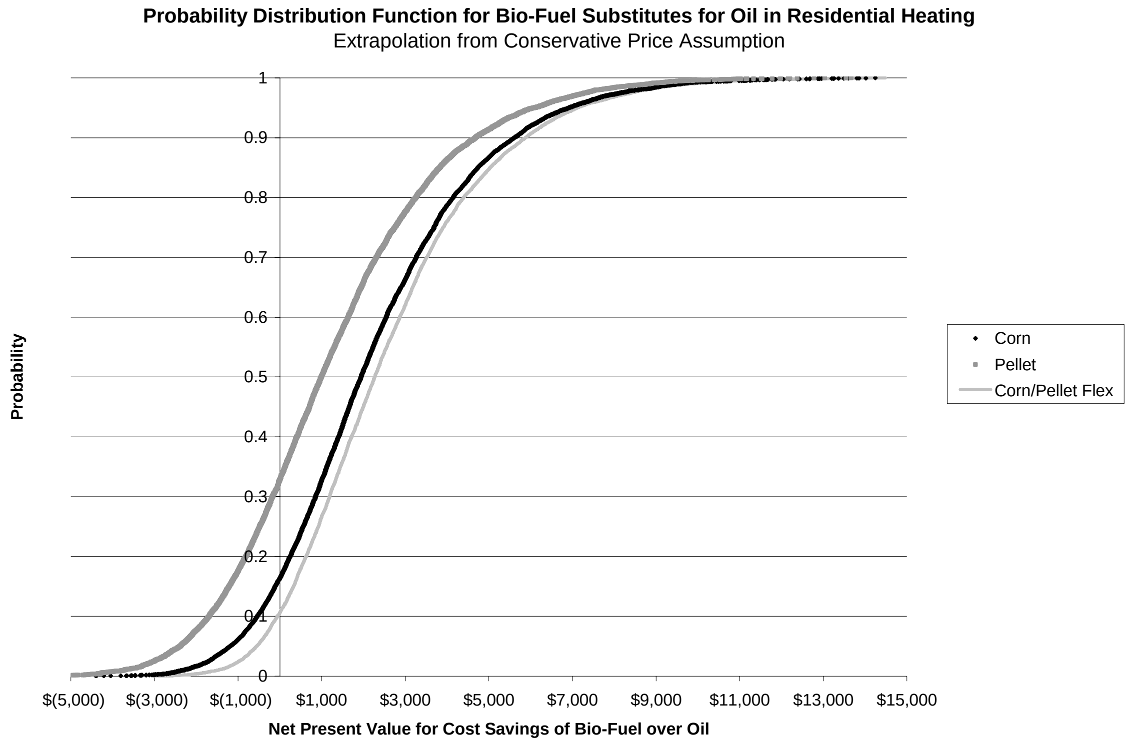


Figure 21: Probability Distribution Function for Residential Furnace Net Present Savings from Bio-Fuel Consumption Relative to Oil, Extrapolated from "Expected" Fuel Prices

A similar analysis shows the expected net present savings for switching a commercial heat consumer from oil use to bio-fuels. The analysis assumed 526 GJ_{heat}/year consumption and that commercial heating oil prices were $2/$GJ_{heat}$ lower than residential oil prices, which is consistent with historical trends. This analysis shows the average net present savings using conservative extrapolations for corn and oil was only $9,070 with a standard deviation of $18,367. The value of fuel flexibility was much greater for commercial users than for residential consumers. Adding pellet flexibility to the corn furnace increased the net present savings by $2,850. Adding the flexibility to burn either oil, corn, or pellets increases the net present savings by another $2,900 to a total net present savings of $14,820 with a total standard deviation of $14,810. Assuming that corn burning is not an option due to high prices, the net present savings of a pellet/oil flex fuel furnace was only $9,740 relative to an oil furnace alone. For the greatest consumers, educational buildings, the most conservative pricing scenario predicts that a pellet burner with the flexibility to use oil has an expected net present value of $35,800 with a standard deviation of $46,900. Thus in the conservative case, it is most worthwhile to add fuel flexibility to commercial and institutional sized furnaces.

5.1.4 Economic Modeling Summary

The economic viability of solid bio-fuel heating is dependant upon the ability of fuel savings to pay back the capital investment. Static modeling provides a fast and flexible tool to view the impact of pricing and consumption rate on the maximum amount that a consumer should be willing to pay for a solid bio-fuel heating system. Given the 10% discount rate and 15-year life span assumption, the net present savings of any system is represented by:

$$[\text{Net present Savings}] = 7.5 * \{[\text{Price of Oil } (\$/GJ_{heat})] - [\text{Price of Bio-Fuel } (\$/GJ_{heat})]\} * [\text{Annual Fuel Consumption } (GJ_{heat}/\text{year})]$$

The dynamic calculation method enables greater understanding of the financial risks inherent solid bio-fuel heating system ownership. At the 2005 pricing levels, the likelihood of a consumer losing money on a $2,500 upgrade that enabled solid bio-fuel heating was 13%. For commercial users, a $5,000 upgrade would have only a 4% likelihood of loss. At these pricing levels, the economic incentive for adoption is very strong. The economic incentives are less when making more conservative assumptions, such as lower oil prices ($37/barrel) and prohibitively high corn prices.

Furnaces capable of burning either oil or pellets are more valuable under conservative pricing assumptions. In the conservative pricing case, a pellet and oil flexible fuel furnace will save the average residential consumer $1,900 over its lifetime and the average commercial consumer $9,700 over its lifetime. Without the added flexibility of using oil when heating oil prices are lower than pellet prices, the average residential consumer would save only $1,340 and there would be no expected net present savings for commercial pellet heat users. The cost of fuel flexibility between solid bio-fuels and oil may be significant for new heating systems due to the costs of two separate handling systems (liquid and solid). Those consumers that already have oil-heat may benefit more from a flex-fuel system since the oil storage is already paid for and installed.

5.2 Potential Solid Bio-fuel Impact

The preceding sections show that solid bio-mass heating can compete with oil heating systems economically. The following section reviews the non-economic costs and benefits of solid bio-fuel heat, including energy security, carbon dioxide emissions, and other environmental factors. These three aspects of solid bio-fuel heat are then compared with other alternative energy technologies such as ethanol and hybrid vehicles.

5.2.1 Energy Security

Oil is by far the largest primary energy source commodity imported into the United States, though natural gas imports are increasing. Technologies that reduce oil imports thus have the greatest impact on U.S. energy security. The preceding life-cycle analysis shows that solid biomass heat displaces 7 to 11 times more oil than it consumes. Corn-based heat displaces 7.5 times more oil that it consumes. This oil displacement rate is similar to the oil displacement rate of 6.3 for corn-based ethanol [Shappouri, 2002, p12][2]. Note that this means that one bushel of corn processed into ethanol has only half of the oil displacement capacity of corn-heat, since only half of the corn's energy content is made into ethanol.

Although corn-heat and corn-ethanol displace similar quantities of petroleum, corn-ethanol is more heavily subsidized. Legislated mandates and subsidies for corn-ethanol have already pushed the price of corn over $4/bushel in 2006, making corn combustion less economical. The $0.50/gallon ethanol subsidy translates to $5.65/$GJ_{fuel}$ fuel subsidy, given the energy density of 0.09 GJ_{HHV}/gallon for ethanol [Shappouri, 2002, p2]. Assuming 85% oil-heat conversion efficiency, a $6.54/$GJ_{heat}$ solid bio-fuel subsidy for oil displacement would be equivalent. This solid bio-fuel heating subsidization would pay for over half of the fuel costs, increasing the solid bio-fuel heating system net present savings by $2,980 for the average oil-heat consumer, consuming 60 GJ_{heat}/year. This subsidy on the commercial scale would increase net present savings by over $26,200 for the average commercial consumer (447 GJ_{heat}/year), and over $95,000 for the average educational building (1600 GJ_{heat}/year).

Unlike oil displacement from corn-ethanol use, the scale of oil displacement from bio-heat is limited by demand rather than feedstock supply. The total demand for heating oil in the United States was 0.61 EJ for residential heat in 2001 [EIA, 2001] and 0.25 EJ for commercial heat in 2003 [EIA, 2006A]. Thus a maximum of 0.86 EJ of oil may be displaced by solid bio-fuel consumption. This represents 2% of the total petroleum products consumed in 2000 by the United States and 2.5 times the energy consumed in

[2] The oil displacement rate from corn-ethanol is regularly contested. The Shappouri study was used throughout this document, specifically in the calculation on oil consumed in corn production for solid bio-fuel heating. Over 75% of the oil consumed for corn-heat is from production. Therefore, treating the oil displacement capability of corn-ethanol and corn-heat as identical is fairly consistent, even if the oil consumed for ethanol production changes significantly.

the form of ethanol in 2004 in the U.S. [EIA, 2006]. Although the energy security impact of corn-heat or pellet-heat is relatively small it is just as effective as corn-ethanol for displacing petroleum consumption and can already utilize cellulosic feedstocks such as wood and switchgrass.

5.2.2 Greenhouse Gas Emissions

The life cycle of solid bio-fuel production and distribution releases much less carbon dioxide, a major greenhouse gas, than heating oil. Solid bio-fuel heat releases 72-78% less CO_2 than heating oil for the equivalent amount of delivered heat. Each GJ of heat converted from heating oil to solid bio-fuels saves over 17 kg of carbon emissions. Thus, for a $100/ton carbon tax, the cost savings of solid bio-fuel heat relative to heating oil is $\$1.7/GJ_{heat}$. The cost savings from solid bio-fuel heating system ownership under a $\$100/ton_{carbon}$ tax increases the expected net present savings for average home and commercial heating by $776 and $6,800, respectively. This savings quantity implicitly assumes that the cost of solid bio-fuel production increases with the carbon tax, proportional to the fossil fuels consumed during bio-fuel production and distribution.

Heating with corn releases less CO_2 than using that corn to create ethanol. While carbon dioxide emissions from bio-heat are approximately one-fourth of the emissions from oil-heat, the CO_2 emissions from producing ethanol are approximately equal to the CO_2 emissions that would be produced by an energy equivalent amount of gasoline [Farrell, 2006, p507]. Fees for carbon dioxide emissions thus improve the economic viability of corn-heat while they offer little or no net benefit for corn-ethanol economics.

5.2.3 Environmental Factors

Although carbon dioxide reduction is a major environmental advantage of bio-heat use, there are other benefits and drawbacks. Heating with solid biomass also changes land use and local air pollution relative to the status quo of heating with oil.

Land use changes caused by bio-heat adoption vary by feedstock type. Waste wood feedstock changes land use by removing more woody materials during tree harvesting. This extra material removal decreases the amount of nutrients that are returned to the soil. Returning ash residue from the combustion chamber to the forest would help this problem. Paying for forest residues also increases the forest industry's profitability, creating an incentive for more aggressive forest harvesting. Increased forest use can improve environmental conditions through better forest management, but without strong regulation, forests might be degraded through increased pressure to use old-growth forests for feedstock.

Using corn as a heating fuel also negatively changes land use. Increasing corn demand increases the number of acres planted to corn. Corn cultivation uses energy and chemicals intensively. Converting marginal grasslands to tilled cropland also decreases the carbon sequestered in the soil. This pressure to increase corn production already exists in the form of corn-ethanol subsidization. Given the existing land use change, using the corn for direct combustion would provide more environmental benefits than corn-ethanol.

Switchgrass has a net positive effect on land use change. Switchgrass cultivation requires less water, chemicals, and energy than corn cultivation. Switchgrass also sequesters 0.4 tons-carbon/acre/year more carbon in the ground over the first 30 years, compared to normal cultivated land [McLaughlin, 2002, p2125]. If all of the 0.77 EJ_{heat}/year of oil-heat were replaced with switchgrass pellets, land use changes would result in over 7 million metric tons per year in sequestered carbon, assuming an average switchgrass yield of 10 ton/ha [McLaughlin, 2002, p2126].

Solid bio-fuel heat does contribute more air pollutant emissions than oil-heat. Particulate emissions from solid bio-fuel furnaces are approximately twice those of comparable oil furnaces, at 22 mg/MJ instead of 12 mg/MJ [Johansson, 2004, p4188]. If the full 0.73 EJ of oil heating were replaced by advanced solid bio-fuel burners, the total annual particle emissions would increase by 7,300 metric tons per year. Table 22 shows the cumulative effects for several air pollutants if full scale conversion from heating oil to solid bio-fuel takes place. As a reference, the NO_X emissions of 22,600 ton/year are 7% of the 1993 NO_X emissions for the United States [EPA, 2007A]. Similarly, the extra VOC emissions of 408 ton/year produced by full conversion from oil-heat to solid bio-fuel burners would be about 0.1% of 1993 U.S. emissions [EPA, 2007B]. Although bio-heat emits more methane gas (CH_4) than oil heat and methane is a potent greenhouse gas, the quantities are sufficiently small to be less than 1% of the total greenhouse gas benefit from using bio-heat instead of oil-heat.

Pollutant	Extra Emissions (ton/year)
CO	24,769
CH4	219
VOC	408
PAH	109
Particles	7,285
NOx	22,584

Table 22: Extra Annual Emissions for Full Heating Conversion from Oil to Solid Bio-Fuels in the United States

5.3 Existing Policies and Policy Proposals

Solid bio-fuel heating can provide both benefits and drawbacks relative to heating oil. Government intervention can help to enhance the benefits while limiting the negative aspects. The economic benefits of solid bio-fuel heating are likely to lead to increased adoption in the future. Regulations can ensure that this wide-scale adoption takes place in an environmentally friendly manner, minimizing the negative potential impacts. Assistance by the federal or state governments can also increase the rate of adoption to boost the positive impacts, including energy security and CO_2 emission reduction.

Improper biomass combustion, with its correspondingly high pollutant emissions, has already led to wood and pellet stove regulations at the Federal and State levels. These emission standards are focused primarily on fireplaces and stoves, in some cases explicitly excluding pellet and corn furnaces and boilers. Although no regulations for central heating systems were found, the following section reviews stove and fireplace regulations to establish a possible starting point for regulating the solid bio-fuel furnace and boiler industry.

The United States EPA regulates wood heater emissions with statutes §60.530-§60.539, passed in 1988 and revised in 1995. §60.530 explicitly excludes boilers, furnaces, and cook-stoves from the emission limits, thus solid bio-fuel central heating systems would not be regulated by this statute. It nonetheless offers an interesting view of solid bio-fuel heating regulations, and is often referred to in state regulations.

Within the above-mentioned statutes, §60.532 establishes the maximum particulate emissions for wood stoves. There is a distinction between catalytic combustors and non-catalytic combustors. Catalytic combustors require a lower weighted average emission rate of 4.1 g/hr, relative to 7.5 g/hr for non-catalytic stoves. The catalytic stove restriction is more conservative and thus used as the base for calculation. The 4.1 g/hr rating is fixed, regardless of fuel consumption. A 100 MJ/hour residential furnace would produce particles at the rate of 2.2 g/hour, below the wood stove standard. Thus large solid bio-fuel central heating systems that provide significantly more heat than small heating stoves emit sufficiently low emissions to pass the stove EPA emissions standards.

Many states have adopted regulations to further restrict wood burning, primarily to reduce local air pollutant issues. The states taking action against highly polluting single stage combustion heaters include: Colorado, Washington, and the New England States. Most of these states follow the basic EPA criteria regarding stove emissions criteria. Although sale of non-compliant wood stoves is against EPA regulations, there are many that were put into place before the EPA regulations were passed. Some state regulations include limitations on what days non-compliant stoves can be used. Other regulations restrict non-compliant stove use in densely populated areas while those areas are experiencing high air pollutant levels.

6 Summary

Although technically simple, the solid bio-fuel heating system is complex when considered from field to furnace. This summary reviews the main points explored in the previous chapters. The review illustrates the larger picture of how solid biomass heating impacts the United States. Following the overview section are possible private and public policies that can help improve the existing bio-fuel system.

6.1 Results

Displacing heating oil is easier than displacing transportation fuel since the fuel qualities necessary for stationary heating are so low. The stationary nature of home and commercial heating does not require fuels with the high energy density and superior combustion characteristics of transportation fuels. Thus low grade fuels such as solid biomass or bio-oil are able to enter the heating market. Though bio-oil is economically and energetically competitive with solid bio-fuels, its acidity and carcinogenicity make it dangerous to store. Solid bio-fuel is therefore superior to bio-oil as a heating fuel.

Solid biomass fuels can provide efficient heat that is economically competitive with heating oil. Considering only available technologies, the net system efficiencies for providing space heat are: 52% for wood pellets, 71% for switchgrass pellets, and 74% for corn. The net system efficiency is the heat energy output divided by the sum of fossil and non-fossil fuel energy inputs to produce the fuel. The net system includes cultivation, processing, transportation, and consumption. Much of the energy used in wood pellet production is derived from renewable biomass. The total fuel system displaces 7 to 11 times more oil than it consumes.

The net present savings from heating with solid bio-fuel instead of oil depend heavily upon future oil, pellet, and corn prices, but are generally positive. The net present savings is the net present value of purchasing a solid bio-fuel furnace and it's lifetime of solid bio-fuel minus the net present value of purchasing a new oil furnace and it's lifetime of heating oil. The net present savings determines the maximum amount that a consumer might pay for a bio-heat furnace above the price of an oil furnace[3]. Using 2005 average prices to extrapolate future prices, the net present savings are $6,170 for the average residential customer, consuming 60 GJ_{heat}/year, and $43,400 for the average commercial customer consuming 526 GJ_{heat}/year. A very conservative estimate – oil at $37/barrel and corn completely priced out of the market –still provides an expected net present savings of $1,340 for residential heating. At these conservative levels, flexible fuel systems that enable a choice between oil or pellet heating as prices change become much more important. Even in the most conservative case, flex-fuel systems provided $1,900 and $9,740 in net present savings for average residential and commercial consumers, respectively.

Solid biomass fuels emit significantly less CO_2 than oil, but increase local air pollution. Proper combustion techniques enable an order of magnitude decrease in pollution from traditional wood heating, so the air quality problems normally associated with wood-heat are eliminated with newer combustion technologies. However, air pollution emissions are still roughly double those of comparable oil furnaces. Those differences may be reduced through flue gas treatments such as filtration and catalytic conversion if needed. Net CO_2 emissions from modern bio-heat are significantly lower than oil-heat, reduced by 72-78%.

The technologies required for seamless bio-heat systems exist but must be better integrated. Solid bio-fuel production is already developed, including the ability to use waste cellulosic feedstocks such as forest residues. Solids transportation and distribution

[3] For example, if an installed oil furnace costs $1,000, and the net present savings from owning a solid bio-fuel furnace was $4,000, the consumer could pay up to $5,000 for the bio-heat furnace and break even. If the consumer pays only $3,500 for the bio-heat furnace, a $2,500 premium, then they would save $1,500 over the life of the heating system.

systems already exist and can be leveraged from agricultural and dry-bulk delivery industries. Solid bio-fuel furnace technologies have developed significantly over the past decade and are already available at a $2,500 premium over comparable oil furnaces.

Using corn for heating is more efficient than converting its starches to ethanol. While corn-ethanol production consumes roughly as much energy as it produces, burning corn for heat releases four times more energy than its production and distribution consumes. Although both corn-ethanol and corn-heat displace similar amounts of oil, the corn-heat life cycle consumes much less coal and natural gas. Thus while corn ethanol has a net system carbon emission similar to gasoline consumption, corn-heat emits only one-fourth as much carbon dioxide as oil-heat. Also, corn-ethanol processing utilizes only half of the corn's energy potential, so corn-heat provides twice the benefit per bushel relative to corn-ethanol.

Solid bio-fuel heating offers significant economical and environmental benefits compared with oil-heating and corn-ethanol. The superior economic performance, even without subsidization, makes solid bio-fuel heating adoption likely if there is a reliable infrastructure and if the markets are performing efficiently. Even if adoption does not take place soon due to a sudden oil price decline or biomass fuel price increases, historical pricing trends suggest that a transition is very likely in the future. The next section suggests actions that government or private industry may take to smooth and possibly expedite this transition to solid bio-fuel heating.

6.2 Recommendations

Heating with solid bio-fuels is a cost-effective way to displace oil consumption in the United States while significantly reducing carbon dioxide emissions. The economic benefits to the consumer will increase the pressure for adoption if the heating system usability improves. Improved usability requires not only improved fuel handling and ash cleaning systems, but also a more robust fuel production and delivery infrastructure. The following recommendations advocate steps needed to permit solid biomass use to materially displace heating oil use in the United States. These steps would improve solid bio-fuel adoption, mitigate some negative effects, and increase the magnitude of positive effects associated with bio-heat. The solutions require action by both in private interests and government, both state and national.

6.2.1 Solid Bio-Fuel Industry Recommendations

The following recommendations are actions that the solid bio-fuel industry can take to improve system efficiency and market size. The recommendations incorporate actions to be taken throughout the industry, including heating systems manufacturers, fuel distributors, and solid bio-fuel producers.

6.2.1.1 Improve Technology Exchange

The solid bio-fuel heating industry must improve the consumer usability of heating systems through better technology integration. Although the technologies necessary for automation already exist, manufacturers must make them more user-friendly and reduce costs through better heating system integration. Innovation and technology integration appears to take place at the level of individual producers. Research collaboration and cross-licensing agreements could assist development to increase system automation and usability. Collaborative groups economically benefit their members, providing self-propagating incentives for these groups to grow. The superior designs that emerge from these groups should improve solid bio-fuel heating systems designs and increase consumer adoption.

6.2.1.2 Develop Solid Bio-Fuel Trading Market

Solid bio-fuel producers must establish a more robust fuel trading market to handle the increased customer base and fuel supply. Historically, the pellet fuel market has been a niche market, serviceable through individual contracts. As energy prices increase, the pressures to increase beyond the niche market will also rise. A more robust trading infrastructure is necessary to adapt to the expanding market. The increased demand pressure will also increase the variety of feedstock used. Fuel commoditization can provide better market efficiency to manage this increased demand. Commoditization through improved fuel binning could allow more diverse fuel feedstocks. Rather than just binning by ash content alone, as is the current practice, future binning criteria might include fuel slag temperature, pricing energy content instead of mass, fuel handling durability, and sulfur content.

6.2.1.3 Create Solid Bio-Fuel Futures Market

Upon creation of a more robust solid bio-fuel market, a futures market should be added to decrease fuel price volatility. Pellet suppliers have been unable to meet the recent demand surge, causing pellet prices to increase and fuel availability to decrease. These market disruptions slow solid bio-fuel heating adoption. A solid bio-fuel futures market could increase fuel market stability. A fuel futures market allows fuel suppliers to guarantee their shipments while enabling potential producers to decrease the risks of capital investment in new production facilities. The relatively small capital investment for pellet manufacturing should allow three year futures contracts to dramatically reduce investment risk.

6.2.2 Public Policy Recommendations

Solid bio-fuel market development has both positive and negative externalities that must be controlled by public institutions. The energy security and greenhouse gas benefits require national or even international policies to account for positive externalities. Some of the externalities, however, are local enough to justify state or even municipal government action, such as pollution or production tax benefits.

6.2.2.1 Air Pollution Regulation

Air pollution regulators must consider the effects of increased local air pollution by solid bio-fuel heating systems and regulate accordingly. As a niche market, pellet and corn heating systems have had little effect on local and regional air pollution. A growing market may lead to air quality problems if there are not sufficient incentives to produce low-emission heating systems and fuels. It is beyond the scope of this thesis to determine if the levels of pollution from solid bio-fuel heating are significant enough to require new policies, but there is a significant enough change to warrant inquiries into the potential effects. Policy changes might come in the form of solid bio-fuel furnace and boiler emission and safety certifications, similar to EPA statutes §60.530-§60.539. Certifying emissions instead of combustion technologies ensures a competitive advantage for those producers that provide low pollution burner designs while allowing system design flexibility. Upon certification, the EPA may either make certified systems mandatory, or provide pricing pressures for certified furnace adoption, e.g. tax credits.

Not all pollutant emissions depend upon furnace design, however. Some emissions are dependant solely on the fuel, such as SO_X. The EPA should help to ensure lower future emissions from fuel sources by adopting early fuel quality regulations on fuel contaminants that lead to air pollution, such as Sulfur.

6.2.2.2 Land Use Regulations

Another potential negative impact from solid bio-fuel heating is land use change. Using waste wood increases logging profitability. Though this is a desired outcome for job creation, it also increases the pressure to utilize old-growth forests. This logging pressure requires adaptations to existing forestry regulation to ensure the increased economic pressures are adequately safe-guarded against, both at the state and federal levels.

Conversely, positive externalities associated with land use change do not have regulatory incentives. For example, switchgrass-based fuel production has crop production externalities such as reduced water consumption and increased carbon sequestration. These positive externalities are not realized by the producers, thus they have little economic incentive to grow switchgrass. Federal legislation should provide economic incentives for switchgrass production that are consistent with the benefits associated with their environmental externalities.

6.2.2.3 State Solid Bio-Fuel Production Incentives

The positive economic externalities associated with solid bio-fuel production warrant special consideration in state governments, especially in states with large forest industries. Solid bio-fuel production increases economic activity through jobs created harvesting waste wood, processing into pellets, and distributing. This local economic activity increase should be considered to determine if production incentives would provide a net economic benefit to the state through increased tax revenues and lower unemployment.

6.2.2.4 Solid Bio-Fuel Heating in Municipal Buildings

Local governments should convert large buildings that are heated with oil to solid bio-fuel heating systems where economically viable. Besides providing environmental and energy security benefits, they can also save money from lower fuel costs. Although raw bio-fuels are not explored in this thesis, they should also be considered where locally available since they are lower cost and have even less energy input than processed solid bio-fuels such as pellets.

6.2.2.5 Alternative Fuel Subsidies

Although consumers can benefit economically from solid bio-fuel heat without subsidization, short-term subsidization may enhance solid bio-fuel heating system adoption rates. Federal subsidies would also provide a more level playing field with existing fuel subsidies. For example, the large subsidies and blending mandate for corn-ethanol have driven the price of corn from its 2005 average price of $1.90/bushel to over $4/bushel. The increased corn prices have effectively taken corn-heat off the market, decreasing the economic benefits of solid bio-fuel heating. Rather than extending that subsidy to solid bio-fuels, the corn-ethanol subsidy should either be removed, or extended to the capital investment necessary for solid bio-fuel heating systems.

A capital subsidy is preferable to a solid bio-fuel subsidy since it acts as an incentive to switch heating systems, but not excess fuel use. For example, a \$5.65/GJ_{Fuel} subsidy for solid bio-heat, comparable with the \$0.50/gallon ethanol subsidy, equates to a \$2,860 capital equipment subsidy for average use by a heating oil consumer. This subsidy could cover the cost differential between consumers purchasing an oil furnace/boiler and one that consumes solid bio-fuels. Capital investment subsidies have already been used for capital intensive alternative energy technologies, such as hybrid car tax credits. Like the hybrid car tax credit, bio-heating system subsidies should have a sunset clause to decrease industry dependence upon capital subsidization, while providing first mover incentives for producers and early consumers. As mentioned earlier, capital subsidization may also be used to enforce emissions regulation, making the subsidy available only to those devices that pass emissions standards.

Besides providing first mover incentives, capital subsidies could also increase consumer conversion rates. The economic analysis in Chapter Five only considered consumers deciding between a new heating system that uses oil or one that consumes solid bio-fuels. Increasing the economic benefits of solid bio-fuel heating will provide an incentive for consumers to replace existing functional oil heating systems with solid bio-fuel heating, which requires a greater economic incentive. The fuel savings from solid bio-fuel heating must equal the total cost of the new furnace or boiler plus installation costs. Providing capital investment subsidies can push people to replace old furnaces sooner, before they are non-functional, increasing the rate of transition towards reduced oil dependence.

Finally, although solid bio-fuel heating systems are not currently competitive with natural gas heat, they may become competitive over time. As natural gas demand outpaces supply, the prices may increase to make solid bio-fuel heating economically competitive. Providing incentives for solid bio-fuel heating infrastructure now will prepare the solid bio-fuel heating industry to compete with natural gas heating, a much larger market, in the future.

6.3 Conclusions

Though we must eventually find viable alternatives for petroleum in the transportation fuel market, there are economically attractive alternatives to non-transportation petroleum uses today. The easiest fuels to replace are those that provide the lowest-grade energy. Stationary heating is one example of this low quality petroleum use. Heating fuels do not require the portability or high fuel quality that petroleum offers. Instead, heating fuels must only be portable enough to deliver as well as clean enough to burn efficiently with little pollution. Solid biomass fuels satisfy these requirements, meeting the needs of home and commercial heating markets with little upgrading cost.

Two basic fuel types were considered for displacing petroleum heat: solid bio-fuels and bio-oil. Bio-oil production is efficient and low-cost, but the resulting product's carcinogenicity and acidity is too dangerous for serious consideration in home heating. It may, however, be used in large commercial and industrial applications, though that is not considered in this analysis. Solid bio-fuels such as wood pellets, switchgrass pellets, and corn are safe, cost-effective, and energy-efficient. Although this analysis considers corn as a fuel, it does not necessarily advocate using food for fuel. The paper does show, however, that if corn is used to displace petroleum consumption, solid bio-fuels are more cost-effective and energy-efficient than corn-ethanol, the dominant use of corn for petroleum displacement today.

Biomass offers a significant addition to global energy supply. However, biomass fuels are inherently limited in quantity, and should be used as efficiently as possible to reduce fossil fuel consumption. Governments and industry should become more involved in expanding the solid bio-fuel heating market to improve biomass fuel use efficiency. Governments can offer incentives for bio-heating system adoption while regulating emissions and land use to minimize environmental damage. The solid bio-fuels heating industry can increase collaboration for design and market development to improve heating system usability and fuel supply stability. Together, business and government can improve biomass fuel use to more effectively reduce fossil fuel dependence.

References

[AER, 2001] U.S. Department of Energy, Energy Information Administration, Office of Energy Markets and End Use. 2001. *Annual energy review 2000.* Pittsburgh, PA 15250-954: U.S. Government Printing Office, DOE/EIA-0384(00), http://tonto.eia.doe.gov/FTPROOT/multifuel/038400.pdf (accessed March 20, 2007).

[Braaten, 1999] Braaten, Ron. 1999. *Opportunities for wood energy for the residential sector: A background document.* Cantera Mining Limited, http://www.canren.gc.ca/app/filerepository/6B5D7DC1DACE4263A9EE042A91C4EC3F.pdf (accessed March 23, 2007).

[BLS, 2007] U.S. Department Of Labor, Bureau of Labor Statistics. 2007. *Consumer price index -- all urban consumers - (CPI-U) -- U.S. city average -- all items.* Washington, D.C. 20212: Bureau of Labor Statistics, ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt (accessed April 9, 2007).

[Bridgwater, 1999] Bridgwater, A. V., D. Meier, and D. Radlein. 1999/12. An overview of fast pyrolysis of biomass. *Organic Geochemistry* 30, (12): 1479-1493.

[Bridgwater, 2000] Bridgwater, A. V., and G. V. C. Peacocke. 2000/3. Fast pyrolysis processes for biomass. *Renewable and Sustainable Energy Reviews* 4, (1): 1-73.

[Bridgwater, 2002] Bridgwater, A. V., A. J. Toft, and J. G. Brammer. 2002/9. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable and Sustainable Energy Reviews* 6, (3): 181-246.

[BTS, 2006] U.S. Department of Transportation, Bureau of Transportation Statistics,. 2006. *National transportation statistics 2006.* Washington, DC: U.S. Government Printing Office, , http://www.bts.gov/publications/national_transportation_statistics/2006/pdf/entire.pdf (accessed March 20, 2007).

[Christianson, 2007] Seed Vac: Bulk Seed Conveyor. in Christianson Systems, Inc. [database online]. [cited March 23 2007]. Available from http://www.seedvac.com/SeedVac.htm (accessed March 23, 2007).

[CA, 2005] Pellet-burning stove owners have a problem: No pellets. 2005. *Consumer Affairs.* December 9, 2005, http://www.consumeraffairs.com/news04/2005/cpb_pellets.html (accessed April 10, 2007).

[Diebold, 2000] Diebold, J. P. 2000. *A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oils.* NREL/SR-570-27613, http://www.nrel.gov/docs/fy00osti/27613.pdf (accessed March 23, 2007).

[EIA, 2001] U.S. Department of Energy, Energy Information Administration. 2001. *2001 residential energy consumption survey: Household energy consumption and expenditures tables*, ftp://ftp.eia.doe.gov/pub/consumption/residential/2001ce_tables/spaceheat_consump2001.pdf (accessed March 21, 2007).

[EIA, 2004] U.S. Department of Energy, Energy Information Administration, Office of Integrated Analysis and Forecasting. 2004. *Documentation for emissions of greenhouse gases in the united states 2002.* Washington, D.C.: U.S. Government Printing Office, DOE/EIA-0638(2002), http://www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2002).pdf (accessed March 21, 2007).

[EIA, 2006] U.S. Department of Energy, Energy Information Administration. 2006. *Renewable energy trends 2004.* Washington, D.C.: U.S. Government Printing Office, http://tonto.eia.doe.gov/FTPROOT/renewables/060304.pdf (accessed March 21, 2007).

[EIA, 2006A] U.S. Department of Energy, Energy Information Administration. 2003. *2003 commercial buildings energy consumption survey: Detailed tables.* Washington, D.C.: U.S. Government Printing Office, http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/pdf2003/allce.pdf (accessed March 21, 2007).

[EIA, 2006B] U.S. Department of Energy, Energy Information Administration, Office of Oil and Gas. 2006. *Petroleum marketing annual 2005.* Washington, D.C.: U.S. Government Printing Office, DOE/EIA-0487(2005).

[EIA, 2006C] U.S. Department of Energy, Energy Information Administration. No. 2 distillate prices by sales type. 2007 [cited March 21 2007]. Available from http://tonto.eia.doe.gov/dnav/pet/pet_pri_dist_a_EPD2_PCS_cpgal_a.htm (accessed March 21, 2007).

[EIA, 2006E] U.S. Department of Energy, Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels. 2006. *Electric power annual 2005.* Washington, D.C.: U.S. Government Printing Office, DOE/EIA-0348(2005), http://www.eia.doe.gov/cneaf/electricity/epa/epa.pdf (accessed March 21, 2007).

[EIA, 2006F] *Voluntary reporting of greenhouse gases 2005 - summary.* 2006. DOE/EIA-0608(2005/S), http://www.eia.doe.gov/oiaf/1605/vrrpt/summary/introduction.html (accessed April 9, 2007).

[EIA, 2006G] *Voluntary reporting of greenhouse gases 2005 - summary.* 2006. DOE/EIA-0608(2005/S), http://www.eia.doe.gov/oiaf/1605/vrrpt/summary/introduction.html (accessed April 9, 2007).

[EIA, 2007] U.S. Department of Energy, Energy Information Administration. Spot prices (crude oil in dollars per barrel, products in cents per gallon). 2007 [cited March 21 2007]. Available from http://tonto.eia.doe.gov/dnav/pet/pet_pri_spt_s1_a.htm (accessed March 21, 2007).

[EPA, 2007A] U.S. Environmental Protection Agency. NOx emissions by source for 1993 & 2008. 2007 [cited March 21 2007]. Available from http://www.epa.gov/air/oaqps/bluebook/noxsrc93.html (accessed March 21, 2007).

[EPA, 2007B] U.S. Environmental Protection Agency. VOC emissions by source for 1993 & 2008. 2007 [cited March 23 2007]. Available from http://www.epa.gov/air/oaqps/bluebook/vocsrc93.html (accessed March 23, 2007).

[ERS, 2007C] U.S. Department of Agriculture, Economic Research Service. Feed grains database: Yearbook tables. 2007 [cited March 24 2007]. Available from http://www.ers.usda.gov/data/feedgrains/FeedYearbook.aspx (accessed March 23, 2007).

[Farrell, 2006] Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O'Hare, and Daniel M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311, (5760) (January 27): 506-508.

[Fiedler, 2003] Fiedler, Frank. 2004. The State of the Art of Small-Scale Pellet-Based Heating Systems and Relevant Regulations in Sweden, Austria and Germany. *Renewable and Sustainable Energy Reviews* 8, : 201-221.

[GGG, 2005] *Gray, Gray & Gray Oilheat Survey 2005: OVERALL RESULTS.* Westwood, MA: Gray, Gray & Gray, LLP., , http://www.gggcpas.com/_files/Overall-Results-2005.pdf (accessed March 23, 2007).

[HBPA, 2007] Hearth Industry Unit Shipments 1998--2005. in Hearth, Patio, and Barbecue Association [database online]. 2006 [cited March 23 2007]. Available from http://www.hpba.org/fileadmin/Statistics/HearthShipmentsUS98-2005.html (accessed March 23, 2007).

[Jannasch, 2001] Jannasch, R., R. Samson, A. de Maio, T. Adams, and C. Ho Lem. 2001. Changing the energy climate: Clean and green heat from grass biofuel pellets. Paper presented at
Climate Change 2: Canadian Technology Development Conference, Toronto, http://www.reap-canada.com/online_library/Reports%20and%20Newsletters/Bioenergy/10%20Changing%20the.pdf (accessed March 23, 2007).

[Johansson, 2004] Johansson, Linda S., Bo Leckner, Lennart Gustavsson, David Cooper, Claes Tullin, and Annika Potter. 2004/8. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment* 38, (25): 4183-4195.

[King, 1999] King, Joseph E. 1999. *Reducing bioenergy cost by monetizing environmental benefits of reservoir water quality improvements from switchgrass production.* , http://www.engext.ksu.edu/biomass/Pelletized%20Switchgrass%20for%20Space%20and%20Water%20Heating.pdf (accessed March 23, 2007).

[McKendry, 2002] McKendry, Peter. 2002/5. Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology* 83, (1): 37-46.

[McLaughlin, 1999] McLaughlin, S., J. Bouton, D. Bransby, B. Conger, W. Ocumpaugh, D. Parrish, C. Taliaferro, K. Vogel, and S. Wullschleger. 1999. Developing switchgrass as a bioenergy crop. *Perspectives on New Crops and New Uses*: 282, http://www.hort.purdue.edu/newcrop/proceedings1999/pdf/v4-282.pdf (accessed March 23, 2007).

[McLaughlin, 2002] McLaughlin, S. B., de la Torre Ugarte,D.G., C. T. Garten, L. R. Lynd, M. A. Sanderson, V. R. Tolbert, and D. D. Wolf. 2002. High-value renewable energy from prairie grasses. *Environmental Science & Technology* 36, (10): 2122-2129.

[Muster, 2000] Muster, Tobias. 2000. *Fuel savings potential and costs considerations for US class 8 heavy duty trucks through resistance reductions and improved propulsion technologies until 2020.* Cambridge, MA: Massachusetts Institute of Technology, Energy Laboratory, MIT_EL 00-001, http://lfee.mit.edu/public/el00-001.pdf (accessed March 23, 2007).

[Oanda, 2007] FXHistory: Historical currency exchange rates. in Oanda [database online]. 2007 [cited March 23 2007]. Available from http://www.oanda.com/convert/fxhistory (accessed March 23, 2007).

[Ohman, 2004] Ohman, M., D. Bostrom, A. Nordin, and H. Hedman. 2004. Effect of kaolin and limestone addition on slag formation during combustion of wood fuels. *Energy & Fuels* 18, (5): 1370-1376.

[ORNL, 2006] U.S. Oak Ridge National Laboratory. Conversion factors for bioenergy feedstock development programs. [cited March 23 2007]. Available from http://bioenergy.ornl.gov/papers/misc/energy_conv.html (accessed March 23, 2007).

[Pastre, 2002] Pastre, Oliver. 2002. *Analysis of the technical obstacles related to the production and utilisation of fuel pellets made from agricultural residues.* European Pellet Centre, ALTENER 2002-012-137-160, http://www.pelletcentre.info/CMS/webedit/images/cmsdoc__19/Part%20IV%20from%20D18%20Report%20on%20critical%20factors-technical%20obsticles_2.pdf (accessed March 23, 2007).

[Patzek, 2004] Patzek, Tad W. 2004. Thermodynamics of the corn-ethanol biofuel cycle. *Critical Reviews in Plant Sciences* 23, (6) (2004-11-01): 519-567.

[PFI, 2007] Industry specifics. in Pellet Fuels Institute [database online]. Arlington, VA, [cited March 23 2007]. Available from http://www.pelletheat.org/3/industry/index.html (accessed March 23, 2007).

[Polagye, 2005] Polagye, Brian L. 2005. Thermochemical conversion of forest thinnings. Master of Science in Mechanical Engineering., University of Washington, http://faculty.washington.edu/malte/pubs/Polagye_Thesis.pdf (accessed March 23, 2007).

[Shappouri, 2002] Shapouri, Hosein, James A. Duffield, and Michael Wang. 2002. *The energy balance of corn ethanol: An update.* AER-814, http://www.usda.gov/oce/reports/energy/aer-814.pdf (accessed March 23, 2007).

[Thek, 2002] Thek, Gerold, and Ingwald Obernberger. 2004. Wood pellet production costs under austrian and in comparison to swedish framework conditions. *Biomass and Bioenergy* 27, : 671-693.

[USDA, 2007] U.S. Department of Agriculture, National Agricultural Statistics Service. Crops and plants. 2007 [cited April 9 2007]. Available from http://www.nass.usda.gov/QuickStats/indexbysubject.jsp?Text1=&site=NASS_MAIN&select=Select+a+State&Pass_name=&Pass_group=Crops+%26+Plants&Pass_subgroup=Field+Crops#top (accessed April 9, 2007).

[USStove, 2007] US Wood Stove. Home page. 2007 [cited April 9 2007]. Available from http://www.usstove.com/ (accessed April 9, 2007).

[Walsh, 2000] Walsh, Marie E., Robert L. Perlack, Anthony Turhollow, de la Torre Ugarte, Daniel, Denny A. Becker, Robin L. Graham, Stephen E. Slinsky, and Daryll E. Ray. 2000. *Biomass feedstock availability in the united states: 1999 state level analysis.* Oak Ridge, TN: Oak Ridge National Laboratory, http://bioenergy.ornl.gov/resourcedata/index.html (accessed April 9, 2007).

[Wenger, 1967] Wenger, Clyde W. 1967. *Pellet mill.* United States Patent 3307501, filed 1967, and issued Mar 7, 1967.

Appendix A -- Binomial Lattice Modeling

Fuel price extrapolations used the binomial lattice modeling approach. The basic premise behind binomial lattice price projections is that each year the price may increase or decrease by some fixed multiplier. If the value increases, it increases by the fixed multiplier *u*. If a value decreases, it does so by a fixed multiplier *d* which is equal to u^{-1}. The probability of the value increasing is *p*, and the probability of the value decreasing is 1-*p*.

For example, assume that $u = 2.0$, then $d = 2.0^{-1} = 0.5$. Also assume that *p*, the probability of the value increasing, is 55%, or 0.55. If the value is 1.0 in year zero, then there is a 55% chance that the value in the year one is 2.0 (1.0 * *u*), and a 45% chance that the year one value is 0.5 (1.0 * *d*). If this is done over successive years, the possible outcomes are as shown in the figure below.

Initial Value	Year of Valuation				
	1	**2**	**3**	**4**	**5**
1	2	4	8	16	32
	0.5	1	2	4	8
		0.25	0.5	1	2
			0.125	0.25	0.5
Possible Values				0.0625	0.125
					0.03125

In each year, the probability of staying on the same row is $p = 0.55$, and the probability of moving down a row is $1-p = 0.45$. In this case, there are $2^5 = 32$ possible paths from the initial value to the value at year five.

Historical fuel prices are used to calculate *u*, *d*, and *p*, which depend upon the average exponential growth, *v*, and standard deviation from that average growth, *s*. The Microsoft Excel® function "LOGEST" was used to calculate the average annual fuel price change (v) over the time history considered. The Excel spreadsheet then calculated the percentage difference of each historical data point from this average curve. The value v is the standard deviation of these values, v is also referred to as volatility in this thesis.

The desired values u, d, and p are functions of s and v, as shown in the following equations. The value Δt is the change in time over the sample period, in this case one year since the values are average annual prices.

$$u = e^{(s*\sqrt{\Delta t})}$$

$$d = e^{(-s*\sqrt{\Delta t})}$$

$$p = 0.5 + 0.5*(v/s)*\sqrt{\Delta t}$$

For the dynamic simulation in this thesis, a 15 year price projection was calculated by increasing or decreasing the previous year's average price by u or d, according to the random probability of the event, p. The resulting oil, corn, and pellet price projections were used to calculate the net present savings from each combination of possible price outcomes. This calculation was done 10,000 times for each scenario, each resulting in a different net present savings.