Direct combustion of biomass : technical and economic feasibility

by Bruce Randal Kinzey

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

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Direct combustion biomass systems often do not return the economic rewards expected because of faulty cost estimations and/or mismatches between the system and the fuels used. "Hidden" costs of fuel collection and system operation may be substantial. Characteristics of specific fuels may negate their use with certain system designs.

Correct evaluation of both technical and economic aspects of biomass combustion systems and fuels is essential for achieving optimal installation results.

These topics are addressed, and a BASIC computer program developed to produce approximate annual cost comparisons between conventional and biomass fuels is included.

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PREFACE

The material contained in this thesis was compiled from research studies of the author and an extensive literature review. Its purpose was to produce an overall picture of the feasibility of biomass-fueled furnace systems for Montana.

The research project was funded primarily by a research grant from the Montana Department of Natural Resources and Conservation. The purpose of the grant was to determine possible optimization techniques for the performance of a commercially-available biomass grain dryer located at the Southern Agricultural Research Center (SARC) in Huntley. Montana. Previous research with this grain dryer (Little, 1984) had shown that it was not economically feasible to operate when the total biomass system and operating costs were compared to those of a propane system. The current research was a follow-up on Little's study and was aimed at improving the biomass system's performance.

Results of the current research were largely similar to those of the previous study. It has been determined, however, that these results apply primarily to the existing grain dryer at the SARC and the conditions and costs of fuel at that site. Rather than duplicating the negative results of the previous report, this thesis attempts to explain and clarify the operating conditions that are required to accomplish efficient use of a biomass furnace system. An introductory literature review was omitted also in efforts to avoid duplication.

The author would like to acknowledge the help of the workers at the SARC, whose inputs greatly aided the research effort, and Al Lien, whose exemplary machinist skills made the system fit together and operate.

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Abstract

Direct combustion biomass systems often do not return the economic rewards expected because of faulty cost estimations and/or mismatches between the system and the fuels used. "Hidden" costs of fuel collection and system operation may be substantial. Characteristics of specific fuels may negate their use with certain system designs. Correct evaluation of both technical and economic aspects of biomass combustion systems and fuels is essential for achieving optimal installation results.

These topics are addressed, and a BASIC computer program developed to produce approximate annual cost comparisons between conventional and biomass fuels is included.

CHAPTER 1

Introduction

The direct combustion of biomass for energy purposes represents an area of large economic potential for small energy-intensive industries like farms. Biomass is a renewable source of energy that is generally in abundant supply on agricultural lands, so it is understandable that attempts are made by farm operators to utilize this energy source. Effective returns, however, are often less than desired because extra costs are encountered that were not at first evident or were ignored in initial analyses. A greater labor input than originally perceived is often necessary, causing further dissatisfaction with installation results.

The decision to purchase a biomass system by an individual is usually influenced by manufacturer's claims of substantial annual energy savings. Estimates of fuel costs for the biomass materials used can differ greatly. Many different assumptions are possible and the resulting total cost is highly dependent on these assumptions. Annual fuel savings often do not include the extra labor and management required for fuel delivery and system operation. Actual costs for a direct combustion biomass system are dependent on the characteristics of the specific fuel to be used, the characteristics of the specific combustion system design, and the conditions of the conventional fuel (price, availability, etc.) at the site of use.

The individual attempting to make a decision on whether or not purchase of a biomass system would be a good investment should be aware of the increased costs and efforts required with using biomass as fuel. Basic knowledge about the combustion properties of biomass fuels and the mechanics of handling and burning biomass will help the individual to understand the reasons why biomass combustion requires extra labor and extra owning and operating costs. Results of research efforts at Montana State University and other locations that have been aimed at reducing or eliminating some of the costs and problems associated with biomass fuels can be useful in helping an individual evaluate the technical feasibilities of different systems.

This research project was limited to a study of direct combustion biomass systems. Other biomass utilization systems (i.e., methane digesters, ethanol plants, etc.) were outside the scope of the research and are not included in this report.

CHAPTER 2

Technical Aspects of Biomass Fuels

The technical aspects of biomass fuels are those qualities or properties of a specific material which affect its use as a fuel. These factors all help to determine the technical feasibility of using the material for fuel purposes. The availability of the material, its energy content, and its combustion and handling characteristics are examples of properties associated with all biomass materials which need to be given careful consideration in order to properly assess a specific material's suitability as fuel. These and other properties that are unique to each material are outlined and discussed in this chapter. Observations are made as to the optimal conditions needed to utilize these materials. The cost of fuels is not covered directly here, although the effects of the technical properties on fuel costs are mentioned. Estimated fuel costs are covered in Chapter 3.

Availability

A particular type of biomass must first be available in a plentiful supply to be considered as a primary fuel source. A fuel that is available only in relatively limited quantities may be useful as a supplementary source, but its usefulness is generally restricted. Limited supplies may result in competition between users and resulting shortages or increased costs at peak periods of use. Under atypical circumstances, a relatively small fuel supply can be used by a single or a few users if adequate control of the supply and subsequent use is maintained. A pertinent example is a system that utilizes grape and apple pomace from processing plants (Mason et al. 1985); such a fuel would probably be used most practically inside the plant in which it was produced. This process would also double as an inexpensive method of waste disposal, and thus could be highly cost effective.

Optimum performance for a particular fuel is usually only obtained with systems that have specialized components designed specifically for that fuel. Characteristics that vary among different materials such as friction coefficients, particle size, and combustion properties require special design considerations. It is usually not practical to design an individual system for a fuel that is in short supply because of design and equipment costs that are specific to that fuel.

It is sometimes possible to use different types of biomass materials in one system by processing them into similar form. Fuels that have dissimilar feeding properties can be made to feed similarly, for instance, by chopping, grinding, or cubing them. This may not be optimal usage, however, because of the additional energy inputs and processing costs required.

The long-term availability of a particular biomass material is likely to be more important than its present availability. Current supply conditions and costs could change rapidly if the demand for a type of biomass increased or if alternative uses for it developed. Conversely, the supply of a particular type of biomass could increase in the future as a result of different cropping practices or new technologies.

Multiple potential sources for a particular type of biomass could be an important consideration in assessing its availability for the future. Reliance on a single source makes the user or users dependent on that source, creating competition between users or a lack of competition between suppliers. Even a user who plans to produce his own fuel should have a secondary source available in the advent of unfavorable circumstances.

The cost of the fuel is directly affected by its availability. A fuel that can be obtained only in limited quantities will likely increase in price with expanded use. In addition, the specialized system components which must be designed for a fuel limited in quantity are more expensive than their more common counterparts. A shortage of a particular fuel may quickly raise its cost to users above the cost of alternatives.

Energy Content

The biomass fuels considered in this study are all composed of cellulitic materials. The potential energy or heat content (Btu/lb) can vary widely between individual fuels, however. The energy that is available from a biomass material is dependent on its density, moisture content, and specific chemical composition. Table 1 lists several biomass materials and the available energy contents for each. These energy levels are listed for oven dry material and for two moisture content (mc) levels of 10 and 20% (wet basis or wb).

It can be seen from the values in Table 1 that moisture content has a significant effect on the net heat available from each material. The combustion of biomass materials actually occurs in three stages:

1) evaporation of moisture; 2) volatilization and burning of volatile matter; and 3) combustion of fixed carbon (Stout, 1984). The first stage, evaporation of moisture, must take place before the second stage occurs. This results in an absorption of some of the available energy in the material by the water as it is evaporated. Obviously, higher moisture content materials must surrender a higher percentage of their energy to this process than those containing lower moisture levels.

Table 1. Average Net Heat Contents (Btu/lb) for Various Biomass Fuels

Fuel / %mc (wb)	0	10	20
Corn Cobs	8477[a]	7514[b]	6552[b]
Corn Husk	7917[a]	7010[b]	6104[b]
Corn Stalks	9552[a]	8482[b]	7412[b]
Soybean Residue	7487[a]	6623[b]	5760[b]
Cotton Stalks	7788[a]	6894[b]	6000[b]
Wood & Wood By-products	9000[c]	7890[c]	6960[c]
Straw	7811[d]	6915[b]	6019[b]

[a] Sumner et al.(1983)
[b] Estimated, using 1150 Btu/lb for evaporation requirement of water.
[c] Johnson et al.(1951)
[d] MSU bomb calorimeter determination.

Moisture in the fuel results in other reductions in the available energy from the material that are in addition to those caused by the evaporation of water. A dry matter loss over time often occurs due to microbial activity within the fuel. Microbial activity within the fuel is encouraged by the presence of moisture. Spontaneous heating within the fuel can also occur, further enhancing biological degradation (Suggs, et al. 1985). Drying of the biomass and maintaining it in a dry condition is essential for achieving the highest available energy output at the time of use.

Corn harvest residues and other materials stored in loose form appear to be very susceptible to dry matter loss. Richey (1982) found that corn stover stored at 13.9% mc lost 10% of its dry matter after six months, while stover that had been stored at 33.4% mc lost 22.6% of its dry matter over the same time period. Smith et al. (1983) conducted a study on ventilated vs. unventilated storage piles for corn cobs and found that the net available energy of an unventilated pile was approximately 10% lower than the net available energy of a ventilated pile after 9 months of storage. Ventilation was achieved by using a fan ducted to the center of the pile. The conclusion was that the difference in energy content between the two piles was mainly due to the increased dry matter loss and moisture level in the unventilated pile.

Studies with round bales have shown that they also suffer dry matter losses when stored. Anderson et al. (1981) found that storage dry matter losses averaged 14% for alfalfa stored outside over one winter. Verma et al. (1983) found that ryegrass bales stored outside in Louisiana for 7 months averaged about 29% dry matter losses, which increased to an average of about 33% after 12 months. The high relative humidity of the surrounding air was probably a major factor in the relatively severe losses found in the latter study.

The dry matter losses for wood chips are probably less than those for straw and stover, because of their more compact and rigid structure which better resists mechanical deterioration. Losses are further reduced because wood chips only require two or three months of storage to dry 20% mc chips to an easily combustible 12.5% mc (Kinzey, 1985). Storage losses can reasonably be assumed negligible for these circumstances.

The net available heat energy from a particular type of fuel may vary for reasons other than moisture content. For example, the heat content listed in Table 1 for oven dry corn stalks (9552 Btu/lb) was for hand-harvested material. Machine-harvested corn stover in the same study was found to contain approximately 20% less total energy (7616 Btu/lb). It was surmised that the probable cause of the difference in these values was that the machine-harvested stover contained sand and soil particles, while the hand-harvested stalks were cut at ground level and were therefore cleaner. Other reasons for differences in specific biomass heat contents include age of the biomass, growing conditions, and variety within species.

Methods of Moisture Removal

It is often desirable to reduce the moisture content of a biomass fuel prior to its combustion in order to increase the net heat output during use. Several methods of moisture removal exist; more than one may be used on a single batch of fuel in some situations.

Solar- or air-drying is the most common method for removing moisture from biomass fuels. All biomass materials have an equilibrium moisture content that is related to the temperature and relative humidity of the surrounding air. Loose fuels like corn cobs or wood chips are typically pile-stored outside for a period of months before their use. Air circulating through the pile will bring the material to its equilibrium moisture content if the storage period is long enough. Straw is generally field-dried prior to harvest, and baled in its dried or equilibrium condition. The equilibrium moisture content may change as surrounding conditions change. Warming ambient temperatures may cause even further drying of the material, or an increase in relative humidity of the ambient air may cause moisture to be regained by the material.

The process of air drying uses direct solar energy to remove the water in the biomass, and can be a very effective method. Table 2 gives the results from an air-drying study on four different fuels stored at the SARC over a period of 6 months.

Table 2. The Moisture Contents (%wb) of Biomass Fuels Stored Outdoors at Huntley, Montana.

Fuel	Sample Location	Date of Moisture Sample 3/28/85	7/5/85	10/5/85
Sawdust-Covered	surface	28.03	25.07	24.44
Sawdust-Uncovered	surface	58.02	51.41	-----
Sawdust-Uncovered	center	40.82	58.95	42.66
Stover-Uncovered	surface	46.56	6.51	22.5
Stover-Uncovered	center	12.71	7.82	-----
Straw-Large Round Bales	surface	17.23	2.99	5.83
" " " "	center	16.01	1.28	-----
Wood Chips-Uncovered	center	-----	20.10	12.37

A storage problem was noted with the corn cob/stover storage pile in this study (listed as "Stover-Uncovered"). Water absorbed from rainfall was drawn to the base of the pile, where it collected, causing a rotting of the cobs and stover. A moisture content determination was not performed on the base of this pile, but the material contained enough moisture that an appreciable amount could be squeezed out by hand. This resulted in a loss of energy from the storage pile, as rotting is a result of microbial activity, which consumes energy.

Surface moisture for all the fuels in the table fluctuated rapidly with ambient temperature and moisture conditions. Rainfall was quickly absorbed into the piles and either drawn to the center or subsequently evaporated. Snow required a longer period to be removed than did rain, because the snow required melting prior to evaporation. In one spring melting period, when it was desired to operate the furnace, straw remaining in the feedwagon had to be disposed of because its high moisture content made it unusable.

The sawdust used in this study also became unusable for fuel purposes because it absorbed and held moisture in a sponge-like fashion. Due to the small particle size of the sawdust, air did not circulate well through the piles, which resulted in extremely high moisture retention. This problem was most evident in the uncovered storage pile. Because of the moisture problem, and because of a tendency for wind to blow away portions of the pile, it was determined that the use of sawdust as fuel will require covered storage (preferably building storage).

There are various methods for non-solar moisture removal. These methods are usually used only when the biomass fuel is needed immediately. Air-drying the fuel requires a relatively long period of time, and generally will not be appropriate if the fuel is required soon after harvest.

One method for drying biomass is direct heating using either conventional fuels or a portion of the biomass itself. Other methods may use recovered waste heat from grain drying or other heat-intensive processes. Morey et al. (1982) noted that using biomass to dry corn cobs often caused fires when sparks in the exhaust air set fire to the drying cobs. This problem would require the use of a heat exchanger or other system modification.

Morey (1983) found that supplemental heat from a propane torch was required in order to obtain a satisfactory heat output when using corn cobs at their harvest moisture content of 33%. The supplemental heat required from the propane was approximately 10 to 15% of that amount required to dry the corn with propane alone. Little (1984) found a similar propane requirement in his study with the SARC system while using a high moisture corn cob/stover mixture.

Methods of Collection

Biomass fuels usually require some method of collection by the user, as opposed to conventional fuels which are generally delivered on-site. The methods used to collect the biomass from the field or elsewhere will vary with the type of biomass, intended use of the biomass, and the preferences of the biomass producer. Collection may be as simple as hauling and storage of a truckload of wood chips, or it may entail a great deal more effort, as in the processes of harvesting, drying, grinding, and storing of a crop residue.

Collection of crop residues for fuel purposes may or may not occur simultaneously with the crop harvest. If the biomass is to be gathered in loose form (such as corn cobs), it is usually most practical to accumulate the biomass at the same time the crop is harvested. In normal harvest procedures, the residues are typically gathered by the harvesting machine, the desired crop material is then removed, and the residual biomass material is discarded onto the field. The harvest efficiency for the crop and residue is usually reduced if the field must be harvested a second time to gather the discarded residue. Biomass harvest processes which are combined with the crop harvest typically employ an auxiliary storage vehicle, such as a trailing wagon behind the harvesting machine, to save the residual crop material as it is discarded. This storage vehicle is then emptied or exchanged as needed.

It may be desirable in some cases to leave the crop residue in the field for a period of time after harvest. Allowing straw to air-dry in the field before baling is one such example. Two or three passes over the field in addition to the crop harvest may be required for this procedure. Normally, the straw and chaff drop directly from the combine to form windrows in the field. A swather may be used to cut additional material and to form larger windrows, although this process is not common in Montana. The straw is then baled after the windrow has dried. The final pass through the field collects and removes the bales. A separate biomass harvest operation is sometimes desirable to give maximum capacity for the crop harvest operation.

Cotton and cotton plants are another example where the crop and residue are harvested separately. It is usually desirable to remove the cotton stalks and roots from the field, rather than to incorporate them into the soil. The plants deteriorate slowly in the soil and have the potential of encouraging soil borne diseases in the subsequent crop (Sumner et al. 1983). The cotton plant is not collected simultaneously with the cotton because it requires about 3 weeks to dry under good conditions after being uprooted from the soil. Typically there are at least three machine operations in addition to the cotton harvest that are required for the cotton residue's removal: 1) uprooting the plants, 2) baling the residue, and 3) collecting the bales.

Biomass harvests that require multiple operations are usually more expensive than those that can be done as part of the crop harvesting process. Baled materials, however, are easier to manage, transport, and store than loose materials, so the extra collection costs associated with baling can offset other costs incurred at a later date.

Materials Handling Characteristics of Biomass Fuels

Most biomass fuels are supplied to or metered into the furnace through a mechanical feeding system. Problems will be encountered with certain fuels when the metering properties are not matched to the specific mechanical apparatus used in the feeding system. Information about the individual fuels' feeding properties is required to assess the feasibility of a fuel with a particular system design.

A property common to all biomass fuels is their surface roughness. Lignins and other structural components of plant material give it considerable rigidity, especially when dried. Exposed edges can be very sharp and abrasive to machine parts that come in contact with the material. The coefficients of friction for several biomass materials are given in the ASAE Standards 1985. These coefficients of friction are proportional to the conveying and sliding forces of biomass encountered in a moving system.

Binding and clogging of the fuel in the feeding system is common, especially where the biomass comes in contact with flow obstructions and rotating parts. Fuels that have relatively low density, like straw, are particularly subject to wrapping and plugging. Individual straws or clumps of fuel may stop moving when they come in contact with a stationary surface, or they may intertwine and "bridge" over the top of moving surfaces. The clump of fuel that has come to rest can in turn become a stationary surface to further impede flow. Long, flexible materials, again using straw as an example, exhibit a tendency to wrap around rotating parts. The presence of surface moisture on the biomass or the machine increases adhesive forces, compounding these problems.

Higher density fuels like wood chips may also produce feeding problems. These fuels neither compress nor separate easily. A hard chunk of fuel of this type can quickly become wedged between moving components and stall the system.

Biomass fuels are bulky, which makes them difficult to meter accurately. The apparatus which separates portions of the fuel from the feedwagon prior to feeding them into the furnace must cover a large area to assure good contact with the fuel. The actual amount of fuel in contact with this apparatus at any particular time can vary and thus the amount of fuel subsequently separated can also vary. High amounts of fuel introduced into the feeding system at one instant are what typically cause the clogging and bridging problems.

Emissions

The combustion of biomass materials produces gaseous and solid compounds which are then released as exhaust. It is important to know the products of combustion in the exhaust so that its pollution effects can be understood.

The combustion process is the rapid chemical combination of oxygen with the combustible elements of a fuel. In agricultural crop residues, the combustible elements are primarily carbon, hydrogen, and metallic elements such as potassium and sodium. The chemical products produced from combustion are usually carbon dioxide, water, and metallic oxides. Complete combustion of hydrogen and carbon follow the reactions:

$$2H_2+O_2 \rightarrow 2H_2O + 6.11\text{x}10^3 \text{ Btu/lbH}_2$$

$$C+O_2 \rightarrow CO_2 + 14.1\text{x}10^3 \text{ Btu/lbC}$$

The actual metallic oxides produced in a combustion process depend on the particular fuel burned. The ultimate chemical analyses for corn stover, Douglas Fir bark, straw, and pine sawdust are shown in Table 3. The analyses for the ash from corn stover and Douglas Fir bark are shown in Table 4.

The emissions from a particular fuel during combustion can warrant limitations on its use. Standards imposed by governmental agencies or individuals can restrict a fuel's use until it is no longer economically feasible.

A common application for biomass combustion systems is in the process of drying perishable grains for sale or storage. A typical direct fired grain dryer incorporates the combustion furnace exhaust with ambient air, forcing the resulting mixture through a storage bin containing the wet grain. The grain is thus directly exposed to the chemical compounds produced by the combustion of the biomass. Some of these exhaust products may have properties that are harmful or undesirable in connection with the subsequent use of the dried grain.

Table 3. Ultimate Chemical Analyses for Various Biomass Fuels (%)

Biomass Type / Component	Douglas Fir[2] bark	Corn Stover[1]	Pine Sawdust[2]	Straw[2]
Carbon	56.2	42.48	51.8	36.0
Hydrogen	5.9	5.04	6.3	5.0
Oxygen	36.6	42.65	41.3	38.0
Nitrogen	0.1	0.75	0.1	0.5
Sulfur	----	0.18	----	NS
Moisture	----	4.94	----	NS
Ash	1.2	3.96	0.5	4.75

[1]Stout (1984) NS- Not Specified
[2]Johnson et al.(1951)

Anderson et al. (1983) conducted a study of the effects of furnace emissions on dried corn, and found that two groups of compounds are of concern. The first group, nitrous or nitric oxides, can produce compounds on the grain surface which have toxic effects on animals and man in high concentrations.

Table 4. Analyses of Ash for Corn Stover and Douglas Fir Bark (%)

Material Compound	Douglas Fir[1] bark	Corn Stover[2]
Silica	13.9	72.15
Iron as Fe_2O_3	4.4	4.69
Titanium Oxide	0.4	0.22
Alumina	8.7	4.3
Manganese	0.3	----
Calcium Oxide	51.4	5.15
Magnesium Oxide	3.2	3.92
Sodium Oxide	5.3	1.29
Sulphate	2.9	0.15
Chloride	0.4	----
Carbonate	7.3	----
Potassium Oxide	----	4.41
Phosphate	----	1.05
Unaccounted for	1.8	2.67

[1] Johnson et al. (1951)
[2] Stout (1984)

The second group, polynuclear aromatic hydrocarbons (PAHs), are of even greater concern. These chemical carcinogens are possibly the major cause of human cancers. Benzo(a)-pyrene (BaP) results from the incomplete pyrolysis of organic materials and appears to be one of the most active carcinogenic agents to which man is exposed. BaP levels on some of the grain samples tested in Anderson's study reached 2 ppb during drying. Anderson stated that these samples exceeded various European standards for the maximum BaP levels for smoked foods of 1 ppb.

In addition to possible carcinogenic-compound deposition, biomass exhaust sometimes leaves a noticeable odor on the dried grain. If a person grading a sample of grain notices what he considers to be a commercially objectionable odor, he may judge the grain to be "sample" grade, which could substantially reduce its value. "Sample" grade grain is not saleable in the commercial market, so any value for it would have to be found elsewhere. It was determined in Anderson's study mentioned above that drying the corn with high moisture content fuel at a low furnace output is what generally produced sample grade corn. Problems associated with using the energy from biomass combustion because of particulates and gaseous compounds in the combustion exhaust must be controlled through furnace modifications. Methods for modifying furnace construction and the combustion process to control emissions is discussed in Chapter 4.

The environmental impact of widespread use of biomass for fuel is also a factor to consider as a result of its emissions. Combustible solid fuels like coal and wood have often caused air pollution problems where they have been used extensively. Densely populated areas or those areas which have a geographically-enclosed air supply (i.e., surrounded by mountains) could experience similar pollution problems if the direct combustion of other biomass for energy purposes became common. Pollution standards could be a limiting factor for the use of biomass in some communities.

CHAPTER 3

Biomass Fuel Costs

The allure of biomass as a fuel source is partly due to the widespread belief that it is a cheap or even "free" source of energy, and that the costs associated with using biomass for fuel are present whether it is utilized or not. To a certain extent, this may be true. However, there are extra costs incurred as a result of the decision to use the biomass as fuel; these extra costs must be recognized to determine the true energy cost associated with the use of biomass fuels.

The amount of agriculturally-related biomass produced annually in the U.S. is estimated to be 400 million tons (USDOE, 1983). Much of this residue is considered a waste product, requiring some means of disposal. Residue disposal entails cost, and it is intuitive that the most favorable condition is obtaining an economic value for this waste product to help recover some of the disposal cost.

The cost of conventional energy sources has increased dramatically since 1971. Biomass products contain a fair amount of energy, therefore it is natural to assume that biomass utilization as fuel can help to offset both the cost of energy and the cost of residue disposal. However, the utilization of biomass as fuel introduces extra costs not entirely apparent at first glance. The purpose of this chapter is to describe most of these costs, and provide comparisons between various biomass fuels and comparable amounts of conventional fuels. Only fuel costs will be covered in this section, as system costs are covered in

Chapter 5.

Collection Costs

One of the first costs associated with the utilization of biomass is the cost of collecting the fuel. "Collection" refers to the processes of removing the biomass from its growing environment, packaging it into usable or transportable form (where applicable), and storing it for future use or transport. Many different processes can be used as separate or combined operations, depending on the biomass type and the methods used for collection.

The biomass fuels produced at the SARC consisted of two types: winter wheat straw and a corn cob/corn stover mixture. Corn cobs are a widely used source of biomass energy, and a considerable amount of research has been conducted on their use as fuel. The cob/stover mixture at the SARC was collected simultaneously with the corn harvest, using a combine attachment and a trailing wagon to catch the biomass material as it was discharged from the combine's sieves and straw walker. An extra tractor and operator were required to transport and unload the collection wagons. The harvest time was increased approximately 13% when harvesting the additional biomass, due to the heavier load of the additional biomass and the extra time required to exchange the trailing wagons. The biomass yield was calculated to be approximately 2400 lb/acre, or 2400 lb/hr at a total harvest rate of about 1 acre/hr (Little, 1984). The collection cost for the cob/stover mixture at the SARC has been estimated at $44/ton. This assumes a combine operating cost of $89/hr, a tractor operating cost of $23.55/hr, and a wage rate of $10.00/hr. The cob/stover fuel is clearly not "free". For a uniform net harvest heat content of 4745 Btu/lb (harvested at 33% mc), the collection cost translates to $4.60/million Btu. Storage costs are not included in these figures, because the cob/stover mixture was pile-stored outside, and no value was attached to the space occupied by the pile. Storage costs would have been added if there had been other uses competing with the storage pile for this space, or if some type of housing structure had been used.

Winter wheat straw, the other fuel produced at the SARC, has an economic advantage over many other biomass fuels. The costs shown above for the cob/stover mixture are extra costs required to salvage the biomass for fuel. Straw, on the other hand, is typically harvested and removed from the field for other reasons. For many straw-producing crops, the straw must be removed for disease and pest control or to facilitate crop rotations. The cost for collection of the straw is often therefore a necessary expense associated with the crop production. The cost of collection under these conditions would not be associated with the straw's use as fuel. Under these circumstances, the total cost of the wheat straw as an energy source is relatively low. The collection cost for a 660 lb round bale, such as those baled at the SARC, is estimated to be $3.37 per bale. This is equivalent to $0.74/million Btu for an assumed uniform net heat content of 6900 Btu/lb. The straw's collection costs are much less than those of the cob/stover mixture's primarily because the collection operation does not affect the harvest operation. The cob/stover mixture's collection slows down the harvest and the cost therefore includes combine operating costs. The straw's collection cost is omitted in fuel cost calculations if the straw harvest was considered necessary for production of the crop. The straw's estimate includes operating costs for the appropriate machinery and labor, but again no storage costs. Rectangular bales would have a necessary storage cost because they require the use of tarps or other cover during storage. Uncovered bales in this form quickly absorb moisture from rain or snow melt and rapidly deteriorate (Jenkins et al. 1985).

Processing the biomass into other usable forms is common. Cubing, chopping, and grinding are three examples of biomass processing operations to aid in its transport and use. Processing the biomass represents an energy input, and therefore adds another cost to the fuel. The processing cost may offset other expenditures, however, specifically those related to transportation and handling of the biomass. Jenkins (1983b), presents a method for assessing the optimum cost combination of processing, transporting, and handling the biomass for any situation using network analysis and dynamic programming.

Dobie et al. (1984) found that collection costs for rice straw in California averaged about $22/ton, or $2.00/million Btu. Rice straw must be removed after each season for disease and pest control. The cheapest means for accomplishing this was found to be simply burning the field, with a cost of about $1.50/ton. Incorporating the straw back into the soil cost about $15/ton. They concluded that, "If the straw is of sufficient value for some utilization method to cover the cost of collection and handling, such method of disposal may eventually be economically viable. ...Currently there is no such market." If open-field burning is not an environmentally acceptable alternative, however, then at least a portion of the collection cost can be included as a crop production cost, improving the economics of the biomass harvest.

Other forms of biomass also may have this economic advantage if a portion of the collection cost can be attributed to processes other than use of the material as fuel. The slash and trimmings left over from forestry processes like vegetative control, pruning, tree removal, and right-of-way clearing are examples. Present processes typically leave the material in the woods, burn the material in the woods, or chip and remove it. In the last instance, where the material is removed, the collection cost could be entirely omitted in a fuel cost estimation. Substituting collection for the other processes would add extra collection costs to these materials, but the final cost would be offset by the costs of the original processes that were eliminated. Fridley et al. (1984) has operated a slightly modified large round-baler to collect and package forestry by-products with good success. Collection costs for this system are not yet available and probably will be greater than those found in an agricultural setting. A bale of this type, however, could be expected to possess a higher heat content than other baled materials and thus may prove to be a desirable economic alternative.

Transportation Costs

Transportation and handling produce another set of costs that are encountered with use of the biomass for fuel. Transportation costs are incurred with the movement of the material from the source to the storage site and from the storage site to the location of use. Handling costs include loading and unloading of transport vehicles, loading or stoking the furnace, and any moving of the material at the storage site during the storage period.

Transportation costs can be quite large even if the utilization site is only a short distance from the collection site. The bulk density of biomass fuels is generally low, and it is difficult to utilize the full weight-carrying capacity of transport vehicles without exceeding their storage capacity. Jenkins et al. (1985) found that only 30-35% of a flatbed truck's legal weight limit could be transported per load with 1.6m wide round bales. As the transport distance increases, the transportation cost becomes a greater percentage of the total cost of the fuel. A load of wood chips used for experimental purposes at the SARC was acquired from its source 60 miles away for $21. The vehicle used for transporting the chips required 24 gallons of gasoline for the round trip, resulting in gasoline costs alone of twice the wood chips' cost. The ideal situation is production of the biomass at the same location where it is to be used, thus minimizing transportation costs.

Jenkins et al. (1983a) has presented a computer model to determine the optimum location for a centralized biomass utilization site and the accompanying total delivered fuel costs to that site. Inputs to the model are factors such as collection costs and relative locations of biomass producers in the area of study. The model finds the utilization site which produces the least total delivered cost (collection + transportation) for all of the producers in the area of concern. This model assumes that all of the biomass producers would subscribe to a central power facility.

Handling costs can also be substantial. Machines are generally required to handle biomass, adding machine operating costs to labor. The popularity of large package machines such as big-roll balers is in part due to the fact that these forms are easily and quickly handled by a single worker with non-specialized handling devices. The big round bales at the SARC were loaded into the feed wagon using a tractor and front-end loader. Handling required about 10 minutes of labor and machine operation time per bale loaded. Handling biomass in unpackaged forms, like piles of wood chips or corn cobs, is more time consuming and is less efficient, as loose materials can not be moved as quickly and some of the pile is invariably left each time the pile is moved. At the SARC, loading an amount of wood chips into the feed wagon approximately equal (in heat content) to one big bale required about twice the time as that for the bales, or 20 minutes. The actual time required for any particular situation is dependent on the distance between the storage site and the furnace site.

Jenkins et al. (1985) determined a theoretical loading rate for loading road-sided large rectangular bales of 24 dry ton/hour onto flatbed semitrailers, and an unloading rate of 84 dry ton/hour. The corresponding costs would depend on the wage rate, machine operating costs, and number of workers required.

Operating Costs

Different biomass fuels possess different combustion characteristics, and thus the amount of labor required for the actual combustion process varies with the individual fuel used.

Straw contains a relatively high ash content. The use of straw in a direct combustion furnace results in an accumulation of ash, or slag, in the base of the furnace which must be periodically removed. Problems with operation of the system will occur if this slag is allowed to build up over time. "Slagging and fouling can be a severe limitation in using direct combustion conversion equipment" (Hiler et al. 1985).

Slag was removed from the furnace at the SARC prior to each firing while using straw. It was necessary to enter the furnace to break up the hardened slag, which was then raked out through a small opening in the furnace wall. The number of combustion cycles in which the slag could have accumulated before actually causing any noticeable effects on furnace operation was not determined. Approximately twenty minutes were required for each removal period; any greater length of time required as a result of postponing the cleanings would make this chore very unpleasant. Other fuels, such as wood chips, contain lesser amounts of ash and could be operated for several combustion cycles without cleaning.

The density of biomass fuels also affects their operation costs. Less dense or more bulky fuels, like straw, do not contain as many Btu/ft^3 as higher density fuels, like wood chips. Consequently, the furnace feed wagon will have to be reloaded more often with less dense fuels than with higher density fuels. Lambert et al. (1982) noted that the availability of labor is often critical around harvest time, and the need for continual stoking of a furnace could restrict its use. The time required to reload the feed wagon could be very significant if someone had to leave his position in the field to perform this operation. It was determined in Lambert's study that widespread use of biomass conversion devices can depend on the development of cost effective automatic biomass feeding equipment.

Opportunity Costs

Although biomass is commonly considered a waste product, most biomass materials actually have alternative values. Alternative values for the biomass must also be determined to obtain the true cost for using it for fuel.

The value of agricultural residues that are reincorporated into the soil is a very real value for maintaining soil nutrients and conserving soils. Crop residues reincorporated into the soil are a very effective means of soil conservation. Crop residues increase soil organic matter, improve soil tilth, and also greatly reduce soil erosion by wind and water. The dollar value of the biomass used in this manner is difficult to determine. There is a cost savings in fertilizer applications, soil is preserved, and water retention capabilities of the soil are increased. Assigning a value to these factors is essential, and it must be performed by the individual considering the use of his crop residues as fuel.

A second major alternative use for agricultural residues is as livestock feed. Straw can be used as a portion of cattle rations. Corn and soybean fields can be grazed after harvest as pasture for foraging animals. Little (1984) determined that the corn fields at the SARC had a value of $35/acre as forage pasture. Harvesting the biomass for fuel from these crop residues greatly reduces the value that can be obtained by renting the fields out for this purpose, because the material best suited for animal feed is also the most desirable material for use as fuel.

Assuming these two uses are of paramount importance, the amount of crop residues produced annually in the U.S. still exceeds that amount required for soil incorporation and feed requirements. USDOE (1983) estimates that about 20%, or 80 million dry tons per year could be used for energy production "without adversely affecting soil quality or livestock feed supplies."

There are other alternative uses for agricultural residues that compete with its utilization as fuel. Straw is purchased by dairies and other animal-based industries for bedding and similar purposes. Wood chips and sawdust often have more value as raw materials for paper mills and pressboard manufacturers than as for fuel. Forfeiting these possible alternative values for the biomass material increases the cost of using it for fuel.

The optimum condition for a biomass material for fuel use is that it contain little or no alternative value. Straw cannot always be sold, and it is a common sight to see unused bales deteriorating in the field. Bales of this type can be used for fuel purposes with no opportunity costs entailed. Other materials, like plants uprooted from the soil for vegetative pruning or crop rotations, likely have disposal costs associated with them that can be partly recovered by obtaining an energy value for them. Plant residues such as these can often be obtained for the cost of only hauling them away.

Example values of the costs outlined in this chapter are shown in Chapter 5. The assumptions used to derive these values are contained in Appendix A.

CHAPTER 4

Combustion Systems

The system used to combust biomass fuels must be designed for the chemical and materials handling characteristics of the specific fuel in order to obtain optimum performance. The total biomass system typically includes a combustion furnace, a furnace-feeding apparatus with capacity for fuel storage, and additional equipment as needed for the particular use of the derived heat (ducting, air fans, drying bin, etc.). The word "system" can apply to individual components of the total drying system defined above (feeding system, ducting system, etc.). "Total system" as used here refers to the combination of components as a whole.

The analysis in this chapter is concerned with both the economic and technical aspects of biomass combustion systems, in a manner similar to that used for the fuels analyses.

Technical Aspects of Biomass Systems

The technical aspects of biomass systems must be considered carefully before a system is installed. Topics such as system capacity, space requirements, and materials handling techniques must be integrated to obtain a good system. Factors influencing system costs are considered in the analysis, but specific costs are reserved for Chapter 5.

Heat Output Required

The correct sizing of the total system is dependent on the amount of energy that must be produced. Most combustion systems can be operated over a range of heat outputs; however, the actual amount of heat required from the system should be estimated to aid in system optimization.

It has been shown that biomass furnace systems generally perform best at higher system operating levels (Anderson et al. 1983; Barrett et al. 1983). Systems in these studies that were operated at low outputs had lower overall efficiencies and greater exhaust contamination levels than when they were operated at higher levels. The SARC system has exhibited similar behavior. It can be concluded from this information that the system chosen to provide the required heat should be sized so that it is operating at the high end of its output range. Higher efficiency will result, and excess costs associated with an oversized system will be avoided.

The calculations for the heat required from a system are based on thermodynamic equations that use data such as the mass of water that must be removed from a grain harvest, the temperature and amount of air required to heat a building, etc. Many assumptions are required, such as average ambient conditions, efficiencies, crop conditions, etc. to produce reasonable estimations of the required output. An example system-sizing calculation and the assumptions used are included in Appendix B, and are similar to those used to generate the computer outputs contained in Chapter 5.

Space and Installation Requirements

Biomass systems have special requirements that are different from those using conventional fuels. These requirements must be considered before the biomass system alternative can be decided upon.

There is a very real fire danger associated with the combustion of biomass. There is often a direct line of fuel from the furnace to the fuel-batch storage area; a fire danger is inherently present with this design. The biomass system at the SARC has exhibited a fire problem on numerous occasions. Help from the fire department has twice been required due to the severity of the fire. These fires typically occurred when the fuel delivery system had stopped, allowing the furnace flame to burn back along the fuel line to the fuel batch. Other fires can occur from sparks in the furnace exhaust, which may be either vented into the bin or released to the atmosphere.

Safety precautions make it imperative that the system be installed at a distance from buildings or other combustible materials so that a fire can be quickly controlled. This may be a significant disadvantage on sites where available space in the area of installation is limited.

Space requirements for a biomass system are greater than those for a conventional fuels system even if no fire precautions are needed. The low bulk density of biomass fuels necessitates a relatively large storage space for the fuel batch. An area for the feeding system and furnace must be provided, in addition to the fans and other equipment that are common to all fuels. Access space to permit mechanical handling of the biomass fuel is also necessary.

A typical biomass grain drying system is installed at the SARC, and is shown in Figure 1. The feedwagon, on the right of the photograph, measures approximately 8ft x 16ft. The feed auger on the front of the feedwagon, not completely visible in the photograph, measures 2.5ft x 10.5ft. The furnace is 5ft in diameter, and an additional 40in of space