A Solid Biomass Fuel Ranking Tool

by

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AUTHOR'S DECLARATION

I hereby declare that I, Sam Arsenault, am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Current methods of ranking and selecting biomass fuels are based on short lists of factors. The objective of this thesis is to develop and demonstrate a fuel ranking tool. Existing fuel decision methods and bioenergy technology are reviewed. A fuel ranking tool is then developed and demonstrated. Finally, a procedure for evaluating the thermal efficiency of a pellet stove bioenergy system is developed and implemented.

The tool is designed to be applied by an engineer working in cooperation with the actual fuel user. The user identifies a list of all available fuels which are compatible with their specific energy system. The ranking tool is suitable for users of any sized bioenergy system used for space heating, processing heating, or electricity generation. Through effective communication the engineer lists the user's performance requirements. Requirements considered in this thesis are economic cost of fuels, required storage space, combustion equipment cleaning, and air pollutants emitted during biofuel combustion. Performance indicators corresponding to the user's requirements are then selected or developed by the engineer. Data is then collected by the engineer to be used for the evaluation of these indicators. The indicators are then combined using weighting factors by the engineer to assign a single numerical score to each fuel. These scores allow the fuels to quickly and easily be ranked by the user according to how well they satisfy the user's requirements.

The ranking tool is demonstrated by applying it to a situation of a pellet stove user with 3 available fuel types. The three fuels are ranked in terms of their ability to satisfy the user's requirements with respect to economic cost, storage space, equipment cleaning, certain air pollutant emissions, and supporting the local economy.

A pellet stove thermal efficiency evaluation method is used to determine the percentage of fuel heating value delivered as space heat to the room housing the stove. Natural and forced convection as well as radiation heat transfers are modeled. The procedure results in a thermal efficiency measurement of 62% +/- 1% and 58% +/- 1% for premium wood and wheat straw pellets, respectively.

Acknowledgements

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I also acknowledge Professor Don Gillis, P. Eng., now retired from UPEI. Professor Gillis has been a source of great encouragement to me as I work towards becoming a Professional Engineer. He has taught me to do *most* of my work well but to remember to also have fun.

Dedication

I dedicate this thesis to my family. I was only able to succeed in completing this work because of their amazing support. Their love and understanding enabled me to overcome the numerous challenges I encountered while completing this project.

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List of Abbreviations

Term	Abbreviation
Carbon Dioxide	CO_2
Carbon Monoxide	CO
Construction and Demolition Waste	CDW
Greenhouse Gas	GHG
Greenhouse Gas, Regulated Emissions, and Energy User in Transportation (Developed by Argonne National Laboratory)	GREET
Higher Heating Value	HHV
Lower Heating Value	LHV
Methane	CH_4
Lifecycle	LC
Lifecycle Analysis	LCA
Nitrogen Oxides	NO_x
Nitrous Oxide	N_2O
Particulate Matter	PM
Sulfur Oxides	SO_x
Unburned Hydrocarbons	UHC’s
Volatile Organic Compounds	VOC’s

Chapter 1
Introduction

This thesis develops and demonstrates a tool which can be used by engineers to help any biomass fuel user rank possible fuels according to the fuels' satisfaction of the user's requirements. Some biomass users have access to a variety of fuels which are compatible with their combustion equipment and each offer differences in performance (González et al. 2004). Previous researchers have compared fuels on a variety of criteria, but have each focused on a selection of fuel aspects (Rabier et al. 2006; Sheng and Azevedo 2005; Temmerman et al. 2006). To this researcher's knowledge this is the first bioenergy tool to consider a broader and, more importantly, customizable range of fuel issues.

1.1 Foundational Definitions

Within this thesis a bioenergy system user (or simply a "user") is any person or people responsible for selecting fuels for any existing bioenergy system. No assumption is made that the user has a substantial technical background, although this is likely in the case of most larger systems. It is assumed that the user is able to generate a list of available fuels.

A bioenergy system (or simply a "system") is restricted, in this thesis, to that which provides space heat, process heat, or electricity from the combustion of solid organic material (referred to as biofuels or simply fuels). No assumptions are made about the size of the system. The ranking tool described in this thesis is useful for users of systems which can operate on at least two available fuels.

1.2 Problem Statement

Any biomass fuel has numerous characteristics, benefits, and drawbacks. When bioenergy users select a fuel from a list of possible materials they must consider numerous criteria. Ranking biomass fuels according to their ability to satisfy a given user's requirements is a complex engineering problem because of the numerous properties of each fuel.

1.3 Objective

The objective of this thesis is the development and demonstration of a customizable biofuel ranking tool. The thesis describes the tool in sufficient detail so that a reader with an appropriate engineering background can successfully apply the ranking tool.

1.4 Benefits of Bioenergy

Interest is growing in replacing some fossil fuels, the largest currently used energy source, with biofuels (Wikström 2007; Yücesu et al. 2006). Fossil fuel supplies are finite, non-regenerative, and their production capacity is expected to peak soon or to have peaked recently (Osowski and Fahlenkamp 2006; Winebrake, Corbett and Meyer 2007). Estimates show crude oil becoming an extremely limited resource in 40 to 70 years, natural gas in 50 to 70 years, and coal in approximately 200 years (Pimentel and Patzek 2005; Strehler 2000). Fossil fuel costs have been rising dramatically for a variety of reasons; including taxes designed to discourage their use and increased market demand (Renström 2006; Wikström 2007; Yücesu et al. 2006; Samson et al. 2005).

Anthropogenic activities which release greenhouse gases (GHG's) appear to be causing global climate change (Wihersaari 2005b). Atmospheric concentrations of carbon dioxide and other greenhouse gases are increasing and fossil fuel combustion is considered a major cause of these increases (Lal 2005). Interest in mitigating climate change is encouraging the search for fuels which emit less greenhouse gases over their life cycle (LC). Biomass removes carbon dioxide from the atmosphere during growth and releases the same amount under ideal combustion conditions (González et al. 2004). For this reason biomass fuel is considered carbon dioxide neutral by many researchers (Osowski and Fahlenkamp 2006). Substituting biofuel for fossil fuel will reduce net GHG emissions (Mani, Tabil and Sokhansanj 2004; Wikström 2007).

Numerous forms of biomass are possible substitutes for fossil fuels (Samson et al. 2005). Unlike fossil fuels, biomass has the ability to regenerate (Osowski and Fahlenkamp 2006). According to (Strehler 2000), global biomass growth has the potential to produce 70 billion tonnes of oil equivalent annually, which is roughly ten times the current global annual energy consumption. However, it should be noted that some biomass is in use as food, building material, and some is unattractive to harvest based on economic or environmental reasons. For example, Lal suggests that utilizing even 30% of global crop residue could have negative effects such as soil erosion and CO_2 emissions from soils (Lal 2005). Authors' opinions differ on the total potential for global biomass production. Estimating global biomass production potential is a complex problem and not this thesis' objective.

Biomass fuels have economic benefits aside from their often low purchase costs. Employment income is created by new biofuel industries, as workers are needed to harvest, process, market, and deliver fuel (Gan and Smith 2007). Money spent on local biofuel remains in local economies as opposed to money spent on fossil fuels (González et al. 2006).

As nations shift energy supplies from imported fossil fuels towards local biomass their energy security increases as political instability in oil producing regions has a decreased influence on fuel prices (Lal 2005; Messerer et al. 2007). Introducing biofuel to an existing energy market increases the fuel flexibility available to consumers (Sheng and Azevedo 2005).

Biofuel users may have a selection of fuels available. When multiple system compatible fuels are available it is useful to have a tool for ranking the fuels according to their abilities to satisfy the needs of the user. This allows the best fuels to be identified.

1.5 Thesis Organization

The thesis is structured as follows. In Chapter 2 the current state of the arts in fuel decisions and relevant equipment are reviewed. This includes reviews of general fuel decision methods, combustion emissions, biofuel decision methods, general decision tools, biofuel properties, bioenergy resource assessment, biomass combustion technology, and economic issues.

In Chapter 3 we develop a fuel ranking tool which is the overall focus of the thesis. We begin by discussing the requirements for a list of fuels which the tool can be applied to.

The five step ranking tool is defined on a per step basis including:

- Listing User Performance Requirements
- Defining Performance Indicators
- Collecting Data
- Calculating Performance Indicators
- Combining Performance Indicators with Weighting Factors

Chapter 3 concludes with an example application of the fuel ranking tool.

In Chapter 4 we outline and exemplify a procedure for measuring the thermal efficiency of a bioenergy system. This Chapter is structured to include materials and methods, results and discussion, and recommendations and conclusions. The system selected for study is a pellet stove commonly used for space heating.

In Chapter 5 we draw conclusions about the ranking tool, its effectiveness, and requirements for successful application. We also draw conclusions about the usefulness of the thermal efficiency evaluation procedure documented in Chapter 4.

In Chapter 6 we make recommendations for future applications of the fuel ranking tool. We also reflect on future improvements and additions which could be made to the tool.

Chapter 2

Review of Current State of the Art

2.1 Decision Methods

The purpose of this chapter is highlighting current knowledge of general and biofuel decision tools, biofuel properties, combustion, emissions, and resource assessment. An understanding of previous work in these areas by other authors is necessary to appreciate the biomass fuel ranking tool documented in Chapter 3 and the experimental work presented in Chapter 4.

2.1.1 Fuel Decision Methods

Fuel selections are made according to a variety of criteria. The cost of net energy method is commonly used when finance is the primary concern. In other cases an environmental impact assessment is the basis for fuel selections. Life cycle analyses (LCA) are often focused on either environmental or economic costs. LCA are rarely simultaneously applied to economic and environmental concerns surrounding fuel selection (Zhou, Jiang and Qin 2007).

Zhou, Jiang, and Qin have evaluated the potential of a fuel LCA tool which assesses four different criteria – life cycle economic cost, global warming potential, net energy yield, and non-renewable resource depletion. Their work combined indicators for these four categories using weighting factors to provide a single numerical score for each fuel. These scores can be used to easily rank the fuels according to the four criteria. These authors present a sample application of their tool to a selection of liquid transportation fuels.

A similar system of independent category indicators combined using weighting factors is used in the decision tool presented in Chapter 3 of this thesis. There are significant differences between the decision tool presented in Chapter 3 and (Zhou, Jiang and Qin 2007). The tool presented in this thesis is designed to be used by solid biomass fuel users with existing combustion equipment, whereas

(Zhou, Jiang and Qin 2007) ranks fuels with a focus on energy policies as opposed to addressing concerns of individual fuel users. Also, the tool presented here is easily customized to suit any number of requirements of a specific user (as shown in the example application of the tool in Chapter 3), whereas the previously published tool was rigidly structured and restricted to ranking fuels based on four predetermined criteria. The criteria suggested in Chapter 3 for ranking biofuels are specific to the biofuel industry and include concerns which are of less relevance to liquid or gaseous fuels. Although both decision tools consider life cycle economic cost, the life cycle stages assessed for biofuels in Chapter 3 are different, primarily because an ash disposal stage is necessary for solid biofuels.

Winebrake, Corbett, and Meyer have presented a fuel life cycle energy use and emission analysis for marine vessels (Winebrake, Corbett and Meyer 2007). This LCA is a useful tool for selecting marine vessel fuels based on:

- Emissions:
    - Carbon Dioxide (CO_2)
    - Methane (CH_4)
    - Nitrous Oxide (N_2O)
    - Volatile Organic Compounds (VOC's)
    - Carbon Monoxide (CO)
    - Nitrogen Oxides (NO_x)
    - Particulate Matter (PM)
    - Sulfur Oxides (SO_x)
- Energy Consumption
    - Total Energy
    - Fossil Fuel Energy
    - Petroleum Energy

This LCA borrows core algorithms from the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation model (GREET), developed by Argonne National Laboratory (Winebrake, Corbett and Meyer 2007). The authors present example applications of their LCA to a variety of fuels and marine vessels. This LCA excluded many of the fuel selection criteria identified in Chapter 3. Specifically, economic cost, fuel storage, and equipment cleanliness were not considered.

Wu, Wu, and Wang have performed an energy and emissions LCA on switchgrass derived liquid transportation fuels (Wu, Wu and Wang 2006). This well to wheel LCA made use of the GREET model. This analysis did not consider economic factors related to fuel choice. A major difference between this LCA and the tool outlined in this thesis is that this LCA assumes fuel users have access to relatively new technologies (such as E85 compatible vehicles and hybrids) while the fuel ranking tool presented in Chapter 3 is designed to be applied in situations where users have combustion devices of any design, modern or of older designs.

2.1.2 Emissions

Since combustion emission have been used extensively as a method of comparing biofuels an introduction to some common air pollutants is presented here. Each pollutant is briefly described and some problems the pollutant may cause are listed.

Particulate Matter describes small diameter solids and liquids released by various processes including combustion. During biomass combustion there are three types of particulate matter which may be emitted. These are noncombustible ash, unburned carbon, and liquid drops formed by the condensation of gases (Tillman 1991). PM is broken into categories by individual particle diameter. PM-10 describes matter with particle diameters below ten micrometers and PM-2.5 describes that with diameters below 2.5 micrometers. All PM contributes to visibility problems such as smog and haze. PM is also responsible for soiling buildings and some cases of corrosive and erosive building damage. PM has negative effects on plant growth and contributes to pulmonary and cardiovascular problems in humans (Messerer et al. 2007). PM-2.5 is suspected to be more dangerous to human health than PM-10 because the smaller diameter particles penetrate deeper into the respiratory system (Cooper and Alley 2002, p49).

Sulfur oxides are emitted from the combustion of fuels which contain sulfur. The majority of SO_x is emitted in the form of SO_2 although small amounts of SO_3 are also emitted. Sulfur dioxide has been linked to health problems in humans and plants. Sulfur oxides are a major cause of acid rain which decreases plant growth rates, causes some fish kills, and corrodes some building materials (Cooper and Alley 2002, p51). Most biomass fuels are low in sulfur when compared to other fuels (Tillman 1991).

Nitrogen oxides including NO, NO_2, and other minor species are formed during combustion of fuels which contain nitrogen. They are also formed at high temperatures from nitrogen and oxygen present in combustion air. NO_x is one contributor to smog formation. Nitrogen oxides are harmful to plant and animal life and have been linked to nose and eye irritation, bronchitis, and pneumonia(Cooper and Alley 2002, p51-53).

Carbon Monoxide is formed during incomplete, and thus inefficient, combustion. One cause of carbon monoxide formation is a lack of sufficient combustion air (Tillman, 1991). Carbon monoxide is dangerous to humans because it interferes with the ability to transport oxygen in blood (Cooper and Alley 2002, p55).

Volatile organic compounds, including unburned hydrocarbons, can be emitted from biomass combustion. This occurs if these gases are exhausted rather than burned (Tillman 1991). Some volatile organic compounds have direct negative effects on human health, but a more common concern is the role these gases play in the formation of other pollutants. Photochemical oxidants are formed in the atmosphere by chemical reactions involving volatile organic compounds, nitrogen oxides, and sunlight (Cooper and Alley 2002, p54).

Global climate change refers to the undesired increase in the ability of the earth's atmosphere to retain heat from the sun's radiation. This is potentially the most significant air pollution problem faced by humankind. The combustion of fossil fuels is suspected to be the major energy related cause of increased atmospheric concentrations of greenhouse gases. Greenhouse gases include carbon dioxide, methane, and nitrous oxide. Estimates of the respective contributions of these gases to global climate change are 57%, 12%, and 6%. The amount of carbon dioxide released from biomass combustion is never more than the amount taken up during plant growth, but biomass combustion can release methane and nitrous oxide under certain conditions (Cooper and Alley 1991, p10-13; Jonsson and Hillring 2006).

The list of pollutants presented here is not intended to be exhaustive. Many other pollutants from biomass combustion have been studied (Olsson 2006). As explained in Chapter 3 the fuel ranking tool is customizable with regard to which air pollutants are considered.

2.1.3 Biofuel Decision Methods

Previous publications have compared biofuels on the basis of many individual criteria, but multi criteria analyses are uncommon. Combustion emissions are one possible criterion for comparing biomass fuels (Sippula et al. 2007). LCA methods have been previously applied to solid biomass combustion fuels (Eriksson et al. 2007; Petersen and Kristin 2006; Wihersaari 2005b).

Petersen and Kristin have compared the life cycle Greenhouse Gas emissions avoided when numerous types of wood fuel replace fossil fuels (Petersen and Kristin 2006). The types of wood were logs, sawdust, pellets, briquettes, demolition wood, and bark. The life cycle stages considered were harvest, production, transportation, and combustion. GHG emissions were compared to those which would result from satisfying identical energy demands with fossil fuels. Log GHG emissions were found to be only 14 to 19% of those from fossil fuels, sawdust and bark 6%, briquette and pellet 5% and wood from demolition operations 2%. This LCA allows an easy ranking of these fuels for situations where GHG emissions are the only criteria used for fuel selection.

Olsson and Kjällstrand measured emissions of aromatic hydrocarbons, methoxyphenols, carbon dioxide, carbon monoxide, and nitrogen oxides from the combustion of 3 types of softwood pellets (Olsson and Kjällstrand 2004). These authors noted that if market demand for fuel pellets grows to exceed the supply of mill waste then pellet producers will select new raw materials. The authors suggest that emissions of selected pollutants should be important in the selection of new raw materials for pellet processes. The pellets chosen for their study represented three raw materials – wheat straw, peat, and softwood. The authors present emissions data for the three materials. The authors concluded that softwood pellets had the lowest emissions of organic compounds including methane, benzene, and furan. This is an example of a study which could be used to rank fuels based on a rigid selection of factors, unlike the customizable tool presented in Chapter 3.

Holt, Blodgett, and Nakayama demonstrated the possibility of producing fuel pellets from cotton gin by-products. They also measured emissions from these pellets as well as softwood pellets burned in a residential pellet stove. The stove was similar to the one used for thermal efficiency data collection for this thesis (Holt, Blodgett and Nakayama 2006).

Carbon monoxide, nitrogen oxide, sulfur dioxide, and particulate matter emissions factors are presented in (Holt, Blodgett and Nakayama 2006) for the selected fuels and stove. Emissions factors were significantly lower for the wood pellets than any of the six varieties of cotton gin waste pellets, suggesting that a decision based solely on emissions would favor wood pellets.

Decisions are made to burn biomass as-harvested or in processed forms. Collura et. Al. fired loose and pellet form Miscanthus straw in 25 and 60 kW boilers which were designed for sawdust fuel. They measured CO, Unburned Hydrocarbons (UHC's), SO_2, NO, and dust (PM) emissions (Collura et al. 2006). They also measured thermal efficiency (this efficiency data is presented in Table 3.3 in this thesis as part of a discussion on gathering fuel ranking data). These efficiencies were measured by recording flow rates and temperature increases of boiler tube water as well as masses and heating values of fuels. The authors found that CO and PM emissions were lower for straw pellets than for loose straw. UHC and NO_x emissions were equal for both fuels.

Emissions and efficiency have been shown to depend on fuel selection (Collura et al. 2006; Holt, Blodgett and Nakayama 2006; Olsson and Kjällstrand 2004; Sippula et al. 2007) and also on combustion appliance design (Kristensen and Kristensen 2004). Between 1995 and 2002 government support was available in Denmark for improved straw boiler designs with lower carbon monoxide emissions and higher boiler efficiencies. Carbon monoxide concentrations in exhaust gases were successfully decreased from 5000 to 1000 ppm due to design improvements to air delivery systems. Thermal efficiency rose from 75% to 87% partly for the same reason and partly due to the addition of insulating firebrick (Kristensen and Kristensen 2004).

The dependence of thermal efficiency and emissions on both combustion appliance design and fuel selection has been accounted for in the design of the decision tool presented in Chapter 3. The tool is designed for users of virtually any combustion appliances and solid biomass fuels. This allowance is made through the careful selection of data, discussed in detail in Chapter 3.

2.1.4 General Decision Tools

Decision tools are useful for helping individuals without a scientific background interpret complex technical data. As an example from a different field of study, Paul has published an index of environmental integrity for waterways in the US Mid-Atlantic region (Paul 2003). Paul’s research highlights some important aspects of effective decision making aids:

- Scientists and Engineers must communicate effectively with users to identify the users’ needs
- Technical data corresponding to these needs should be collected in a reliable manner
- Scientists and Engineers may develop systems to make the implications of technical data easier for users to understand

These aspects of effective decision making are incorporated in the design of the fuel ranking tool presented in Chapter 3.

The fuel ranking tool presented in Chapter 3 was not designed by following the Kepner-Tregoe Decision Analysis method. However, the Kepner-Tregoe method warrants mention because of its similar ranking and weighting of objectives (McDermott, 2008).

Other Engineering fields, such as Strengths of Materials, require the use of multi criteria decision methods. Engineering materials can be similar to biofuels because each type has individual characteristics, applications, strengths, and limitations. Selecting a material or fuel can be a challenging problem because there is no single definite attribute of selection (Rao, 2008). A thoughtful selection involves relating material (or fuel) parameters to system level parameters. Matching fuel properties to system requirements is the basis of the Fuel Ranking Tool.

2.2 Fuel Properties

A selection of fuel properties is required for the application of the decision tool. These include moisture and ash contents, heating values, bulk density, and life cycle cost. Below we establish a list of literature which may be useful for estimating some property values. As discussed in Chapter 3, fuel data should only be borrowed from literature if the publication describes similar fuel which has undergone similar treatment. Otherwise, experimental evaluation of fuel properties will be necessary. Literature also provides some documented methods for evaluating fuel properties, as discussed below.

Obernberger and Thek have measured moisture and ash contents, bulk densities, and gross calorific values (also known as higher heating values) of pellets and briquettes made from wood, bark, and straw. Moisture contents were determined by weighing fuels before and after drying at 105 °C. Ash contents were determined by observing a loss of ignition at 550 °C and 815 °C. Bulk densities were determined by measuring the weights and volumes of fuels. Gross calorific values were determined using a bomb calorimeter. A selection of data from this publication is presented in Chapter 3 (Obernberger and Thek 2004).

Moisture contents of biomass samples can be evaluated by drying at a range of temperatures, distillation with xylene or other desiccants, or freeze drying (Samuelsson, Burvall and Jirjis 2006). Samuelsson, Burvall, and Jirjis applied these methods to 20 varieties of biomass. Samples included stem wood, bark, tree needles, sawdust, and agricultural residues. For identical samples a statistically significant difference was found in moisture contents determined by oven drying at different temperatures. Also for identical samples xylene distillation and freeze drying methods provided significantly lower moisture contents than oven drying. This may be due to the loss of volatile compounds during oven drying, which results in moisture content data which is falsely high (Samuelsson, Burvall and Jirjis 2006). Data from this publication appears in Table 3.6 in Chapter 3.

Correlations between biomass composition analysis and higher heating value (HHV) have been evaluated for accuracy (Sheng and Azevedo 2005). Sheng and Azevedo applied a wide range of correlations to a database of biomass materials and found that the accuracy of correlations to proximate analysis (moisture, volatile matter, fixed carbon, and ash contents of fuel) was generally poor. Results from ultimate analysis (moisture, carbon, hydrogen, oxygen, nitrogen, chlorine, sulfur, and ash contents) correlations were generally much better. Chemical analysis (cellulose, hemicellulose, lignin, and extractive contents) correlations generally performed poorly. HHV data will be required for the application of the fuel ranking tool in most cases. Engineers with access to composition analysis data may wish to use correlations to estimate HHV. In many cases it may be easier to obtain HHV's experimentally using a bomb calorimeter.

Bridgeman et Al. have shown that chemical and ultimate analysis data differ significantly for samples of grasses which have been ground to different sizes (Bridgeman et al. 2007). Samples with smaller particle sizes had higher ash and moisture contents while heating values are found to be higher for larger particle samples, likely due to lower moisture and ash contents. This serves as a reminder that fuel data can vary slightly with processing technique. When collecting data for the fuel ranking tool, as discussed in Chapter 3, selection of appropriate data is one key to obtaining reliable fuel rankings.

2.3 Biomass Resources Assessment

Bioenergy resources should be assessed for size so that fuel supplies can be matched to markets with similar demand. This assessment involves using the heating value and available mass of materials to estimate available energy. This step should be completed before the application of the decision tool so that only fuels available in sufficient quantity are ranked. A biomass resource assessment for Prince Edward Island is presented in Appendix A.

Residual crop matter is one of the largest biomass resources in many regions. Lal estimates global crop residue production at 3.8 billion Mg annually. Based on an average heating value this biomass is estimated to have an energy value of 69.9 X 10^{18} J, equivalent to 7516 X 10^{6} barrels of diesel oil (Lal 2005). Some of this material may be used for energy although crop residue is also required for erosion control and soil structure maintenance. Crop residue is considered in the analysis presented in Appendix A.

Transporting biomass over long distances can make fuels economically unattractive, so it is often beneficial to focus on local resources. Pari has assessed the potential for bioenergy use in Italy (Pari 2001). Forest and agricultural biomass production in Italy have a combined mass of approximately 17,206,000 tonnes per year, with an ability to provide 93 TWh of energy. Total Italian energy demand was estimated at 2030 TWh for the year 1995, with biomass providing 41 TWh of this. Pari identifies a potential increase in Bioenergy use of 52 TWh. The analysis presented in Appendix A explores biofuels available from forestry and agriculture on Prince Edward Island.

Forestry residue is a biomass fuel available in large quantities in some areas. Nurmi has compared the mass of logging residues per area of spruce stand harvested in Finland for different harvesting methods (Nurmi 2007b). The methods studied differed in location of felling and delimbing operations with respect to heavy equipment pathways. The methods resulted in logging residue yields of 69.1 to 75.9 wet tonnes per hectare. These figures are of tremendous value to an engineer wishing to estimate the mass of wood which can be harvested from a given area of forest. Yield estimates from a local forest contractor are used in Appendix A to estimate available wood mass.

2.4 Biomass Combustion

Combustion is the most common and highly developed method of converting biomass to energy (Sheng and Azevedo 2005). For this reason the fuel ranking tool is designed specifically for fuel users who operate combustion systems, rather than other bioenergy conversion systems such as anaerobic digestion for biogas production. Biomass combustion equipment is often simpler and cheaper than equipment for other technologies (Sheng and Azevedo 2005).

Solid biomass combustion occurs in four stages, as described in (Tillman 1991):

- Drying
- Pyrolysis
- Oxidation of Volatile Gases
- Oxidation of Char

The drying stage is initiated when heat is transferred to the fuel. This provides energy required for moisture to evaporate. The rate of drying is limited by heat transfer, which is controlled by temperature, geometry, and heat transfer properties (Tillman 1991).

The pyrolysis stage begins when the fuel reaches a threshold temperature, which is about 350 °C for many materials (Tillman 1991). At this temperature combustible and non-combustible gases are released from fuel. The result of pyrolysis is a decreased mass of solid fuel which is then composed mainly of char, a carbon rich material (Erlich et al. 2006).

The third stage of combustion is the burning of volatile gases which were released by pyrolysis. This oxidation is responsible for the formation of most visible flames (Olsson and Kjällstrand 2004).

The final stage of combustion is the oxidation of char. This final process is limited by the quantity of oxygen available and dependant on the char surface area and combustion air flow (Olsson and Kjällstrand 2004).

2.5 Combustion Equipment

2.5.1 Introduction

A variety of combustion equipment has been designed for solid biomass fuels. Appliances range in size from small stoves with thermal outputs in the range of a few kW to large heating plants with outputs of about 100 MW (Kær 2005). Since the fuel ranking tool is only designed to be applied to fuels which are compatible with a given user's existing equipment some basic equipment specifications which can affect fuel selection are reviewed below.

2.5.2 Stoking

A major factor in the compatibility of fuels and appliances is the appliance's stoking system. Manual stoking is the oldest and simplest method. Manual stoking means adding a charge of fuel to a combustion device, usually through a door which is closed during normal operation.
Figure 2.1: Manually Stoked Stove shows an appliance which is stoked manually through a charging door. Manual stoking is performed by hand or using heavy machinery. The restrictions on fuel stoked manually are that it must fit through the door and be within the lifting capability of the person or machine performing stoking. Special thanks to Dr. A Strehler for his permission to use his drawings which appear as Figures 2.1, 2.3, and 2.4.

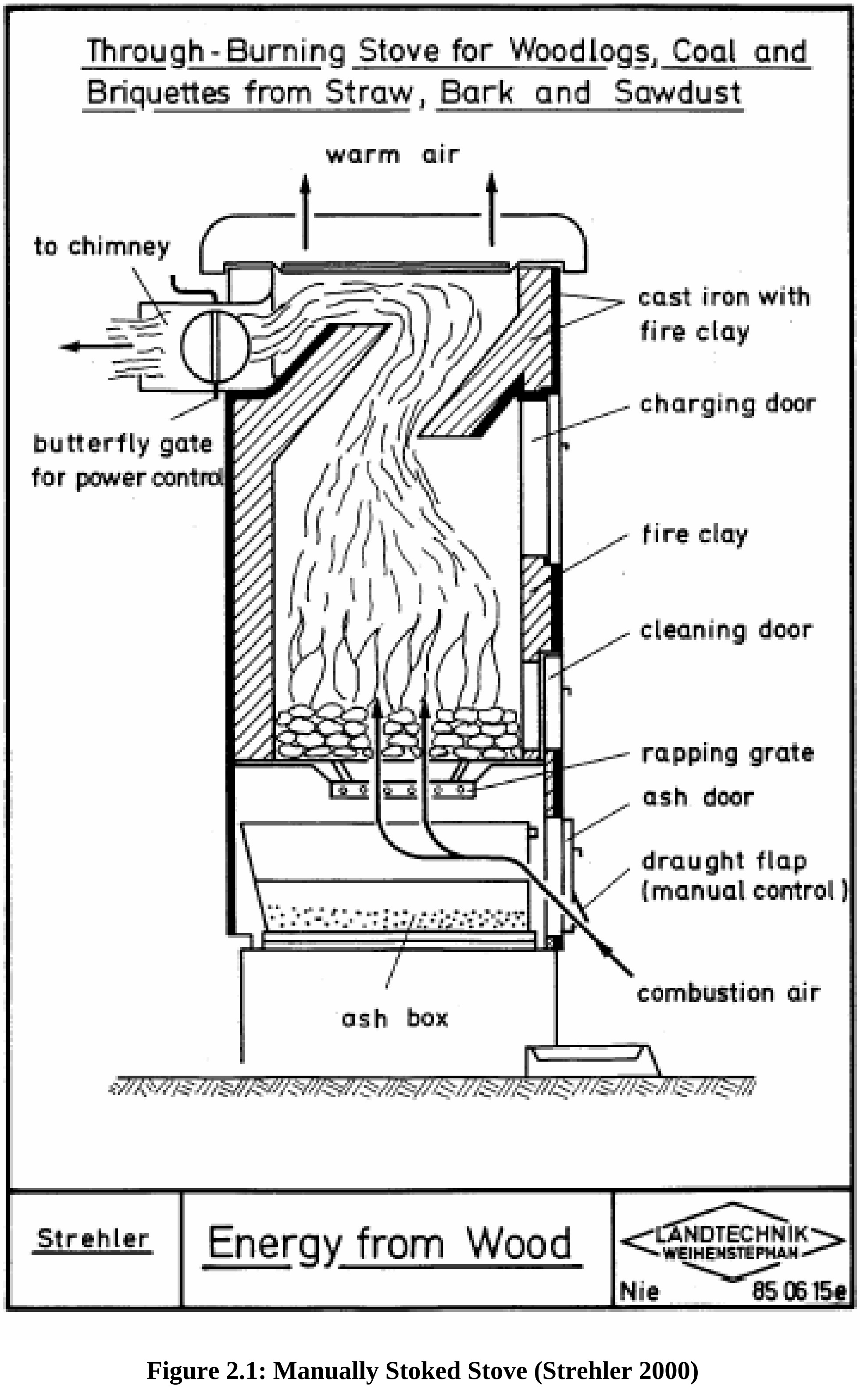


Figure 2.1: Manually Stoked Stove (Strehler 2000)

Figure 2.2: Heavy Equipment Stoking shows a tractor with front end loader manually stoking a straw bale boiler.

Figure 2.2: Heavy Equipment Stoking (Northmoor Trust 2008)

There are numerous types of mechanized stoking. A major advantage of mechanized stoking is the ability to automate the stoking process. The disadvantages of mechanized stoking are increased equipment purchase and maintenance costs. In modern wood chip heating plants combustion equipment problems which occur are often caused by oversize fuel pieces which jam mechanized stoking systems (Strehler 2000). For this reason it is critical to select fuel which is compatible with mechanized stokers, as discussed below.

Figure 2.3: Auger Stoked Boiler shows an example of a common automated stoking system. In this type of system fuel is moved from a storage bin to the combustion chamber through one or more augers. This auger system is commonly used for wood chip or pellet fuel. The restriction placed on fuels by an auger stoking system is that fuel diameter must be a few times smaller than the radius of the auger.

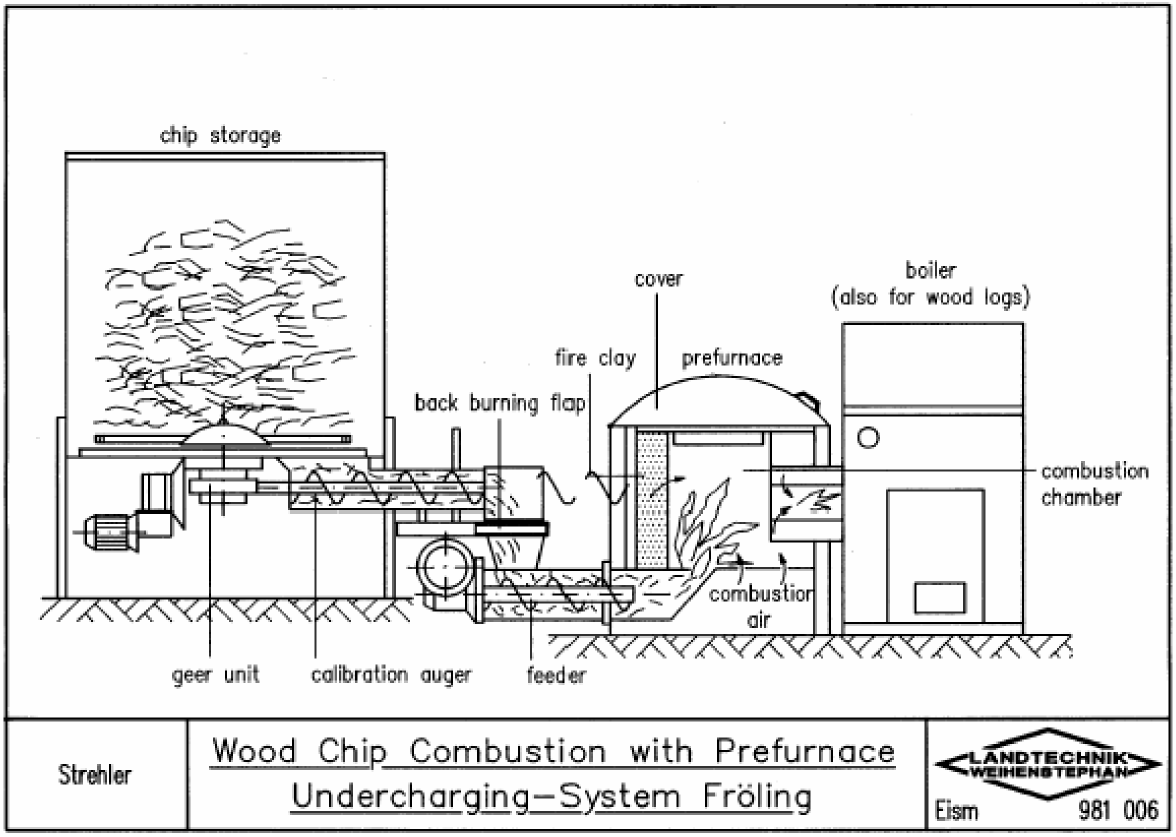


Figure 2.3: Auger Stoked Boiler (Strehler 2000)

A second type of mechanized stoking system is the conveyor belt stoker. In this system fuel is moved from a storage area to a combustion chamber by a rotating belt, which may also have buckets attached. This type of system is suitable for smaller size fuels such as wood chips as well as larger sized pieces such as logs (Strehler 25-40). The restriction this system places on fuel is that pieces must fit on the conveyor (or in the buckets) and through the opening to the combustion chamber. An example of a conveyor system is shown in Figure 2.4: Convey Stoker Boiler. In this system the belts (labeled container discharging) feed fuel to the buckets (labeled fuel charging). The buckets then dump fuel into the combustion device.

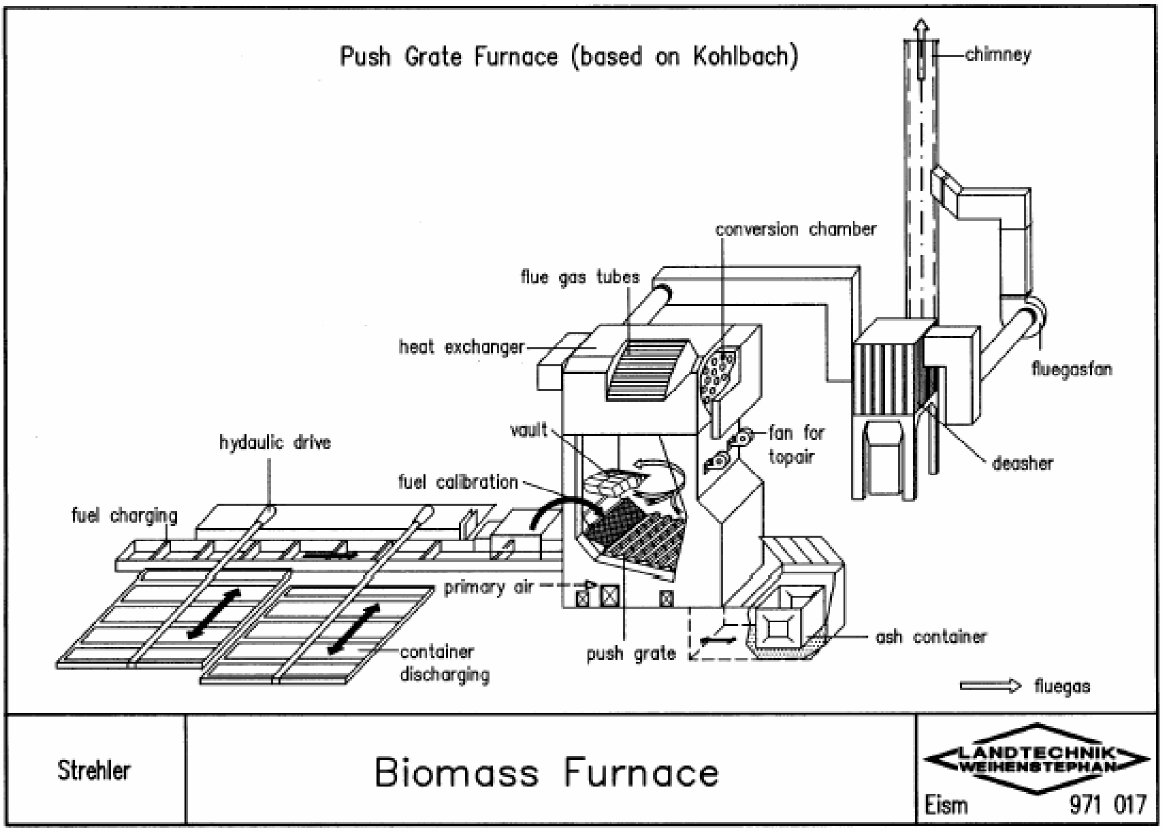


Figure 2.4: Conveyor Stoker Boiler (Strehler 2000)

2.5.3 Air Pollution Control Equipment

Air pollution control is an entire field of engineering but a brief introduction to some methods is presented below since fuel selection can impact the amount of emissions these devices will need to handle. These devices have a wide range of associated costs – some capital investments and some ongoing operating costs. Operating costs for existing air pollution control equipment should be considered when calculating fuel associated costs as discussed in Chapter 3.

The addition of new air pollution control devices may allow emissions to remain below acceptable limits even with a change in fuel which would have otherwise caused these limits to be exceeded.

However, as stated in Chapter 1, within this thesis the fuel ranking tool considers only the capabilities of equipment which the user already has in place.

A variety of equipment has been designed to reduce particulate matter emissions. PM is a major pollutant of interest when considering biofuels (Holt, Blodgett and Nakayama 2006; Jonsson and Hillring 2006; Obernberger, Brunner and Bärnthaler 2006). Cyclones separate particles from a gas stream by forcing flow to spiral through a tube. Centrifugal force causes the particles to move outward and collide with the tube wall. Particles then fall to the tube bottom where they are collected for disposal. Remaining clean gas flow travels upward through the center of the tube (Cooper and Alley 2002, p123).

Fabric filters (also called baghouses in large installations) are also used to control PM emissions. In these devices gas flows through a fabric filter which entrains solid particles. Reusable filters are cleaned by shaking or reversing the direction of airflow (Cooper and Alley 2002, p177).

Electrostatic precipitators flow gas past high voltage electrodes so that PM becomes electrically charged. Particles are then drawn to charged plates. Plates are periodically cleaned by shaking or by impact from rapping hammers (Cooper and Alley 2002, p147).

Wet Scrubbers are also used to control PM emissions. This technology uses water droplets to intercept PM in exhaust flows. Water is then separated from the gas stream, usually by gravity, and treated before reuse or discharge (Cooper and Alley 2002, p215).

Volatile organic compounds may be controlled in a variety of ways. Incinerators (also called thermal oxidizers or afterburners) operate with the addition of extra fuel to transform VOC’s to products of complete combustion. Similar reactions may also be achieved using a catalytic converter instead of an afterburner.

Gas adsorption technology is used to control VOC emission as well. Gas particles adhere to solid porous materials such as activiated carbon. This material is usually packed in a bed which can be introduced to low pressure steam for reactivation when it becomes saturated with VOC’s (Cooper and Alley 2002, p361).

Gas absorption occurs when a gas is dissolved in a liquid. This technology is also called washing or scrubbing and can be used to control PM, VOC, NO_x, or SO_x emissions.

NO_x emissions are often effectively controlled through combustion parameters, such as excess air ratio(Moran and Shapiro 2000). When this is not practical NO_x may be controlled with the use of catalysts which convert NO and NO_2 to pure nitrogen, which is a normal component of air. Adsorption techniques and wet scrubbing may also be effective in NO_x control (Cooper and Alley 2002,).

2.6 Economics

Many factors contribute to the economic aspect of ranking fuels. The life cycle stages of a fuel provide reference points for comparing the cost associated with each stage for different fuels, but the total cost of fuels are far more influential in decision making than any individual stage cost. Within this thesis LC stages considered are production, harvesting, processing, transportation, combustion, and ash disposal.

When considering the production stage in a biomass LC, consideration must be given to the purpose of biomass production. Fuels produced as by-products of other profitable processes have lower production costs than those produced specifically for fuel (O'Connor 2007). Sometimes fuel markets provide a convenient disposal for waste biomass. In these cases the biomass is transformed from an economic liability to an asset (Holt, Blodgett and Nakayama 2006). Alternatively, when a biomass material is produced specifically for a fuel market the entire production cost must be passed on to consumers. In some cases there is competition between the fuel industry and other non-fuel industries to purchase biomass and prices reflect any imbalances between demand and supply which may exist (Gan and Smith 2007; Lal 2005).

Biomass harvesting affects the cost of fuels also. Different harvesting methods can have different efficiencies, causing differences in price (Nurmi 2007). Fuel producers who handle multiple fuels with the same machinery enjoy reduced payback periods on equipment which can be reflected in decreased harvesting costs (Nilsson and Hansson 2001).

Processing is the third LC stage for biofuels. For fuels with high moisture contents during growth, such as wood, drying is an important process which increases the quality of fuel. Fuels which dry naturally will have lower processing costs than those which require a fueled drying process (Tripathi, Iyer and Kandpal 1998). Drying with waste heat can also reduce drying costs, although this method is not as cost effective as natural drying since new equipment installations may be required (Renström 2006; Wolf, Vidlund and Andersson 2006).

Transportation of biomass contributes significantly to overall fuel LC cost. Some experts suggest that a 100 km radius should be used to identify sources of biomass (Pari 2001; Strehler 2000). Often densified fuels (such as pellets or briquettes) hold an advantage over less dense materials because of lower transportation cost per unit of fuel heating value (Mani, Tabil and Sokhansanj 2006).

Combustion of biofuel is the second last LC stage considered in this thesis. Differences in fuel properties, particularly ash content, can result in different equipment maintenance costs (Holt, Blodgett and Nakayama 2006; Obernberger and Thek 2004). This issue is addressed directly in Chapter 3. When air pollution control equipment is present operating costs can vary with fuel choice. Combustion efficiency can vary significantly with fuel selection and will influence the quantity of fuel which must be purchased (Turn et al. 2006). Because of this, comparing fuels on the basis of \$/MJ (gross) is ineffective. The dependence of efficiency on fuel selection is accounted for in the fuel ranking tool, as discussed in Chapter 3.

Disposal of remaining waste is the final LC stage of biofuels. Ash and material collected in air pollution control devices may be disposed of a cost or in some cases ash may be marketable as a soil enhancement material (Obernberger, Brunner and Bärnthaler 2006).

The economic life cycle stages of biofuels discussed above are modeled in the fuel ranking tool presented in Chapter 3.

Chapter 3
Fuel Ranking Tool

3.1 Introduction

This Chapter develops and demonstrates a fuel ranking tool. The tool is designed to rank a list of fuels according to how well each suits an individual user's needs. It is designed to be applied by engineers working in direct contact with bioenergy users. The tool is applied to solid biomass fuels which are burned in existing combustion equipment. Although capital costs for fuel compatible equipment could be accounted for in this tool, within the scope of this thesis equipment is assumed to already be in the user's possession.

Biomass can be burned to obtain energy for space or process heating, or for generating electricity. Bioenergy users include homeowners with heating systems as well as operators of district heating and electric plants. This tool is designed to address the concerns of fuel users as opposed to concerns of other group such as fuel producers, vendors, resource managers, or policy makers. The tool is designed to work for any user regardless of their system's size.

The need for this tool arises from the variety of biomass and the range of users' performance requirements. Different users have a variety of concerns including economic, storage, equipment cleaning, and environmental issues. A wide range of materials are used as fuels, including those listed Table 3.2. In addition to numerous raw materials there are also a variety of processing options for biofuels. For example, wood is available as loose or baled forest residue, sawdust, in cordwood, chip, pellet, and briquette forms. The variety of user concerns and fuels creates a need for a tool which can match users with appropriate fuels based on users' requirements and fuels' properties.

To successfully apply the ranking tool a user must begin with an appropriate list of potential fuels. All fuels considered must be compatible with the user's available equipment. Combustion equipment may differ in the size or shape of fuel pieces it accepts. Some equipment may also have requirements such as maximum ash or moisture contents (Holt, Blodgett and Nakayama 2006). Equipment manufacturers can often provide a list of fuel requirements (Canadian Comfort Industries & Dansons Group Inc.2004a).

Before the application of the ranking tool fuels must also be evaluated to verify that they are available in appropriate quantities for the user's needs. This will ensure that the fuels ranked by the tool are in fact feasible options for supplying the user's energy needs. For smaller systems quantity is rarely an issue but for larger systems energy inputs can be so large that a mixture of fuels may be necessary. The quantity of energy available from a given type of biomass is estimated using available mass and heating value. An example of biomass resource assessment for Prince Edward Island is presented in Appendix A.

This decision tool is applied in five steps. The steps are shown on the following page in Figure 3.1 : Ranking Flow Chart. Figures 3.1 through 3.6 are the original work of this thesis' author.

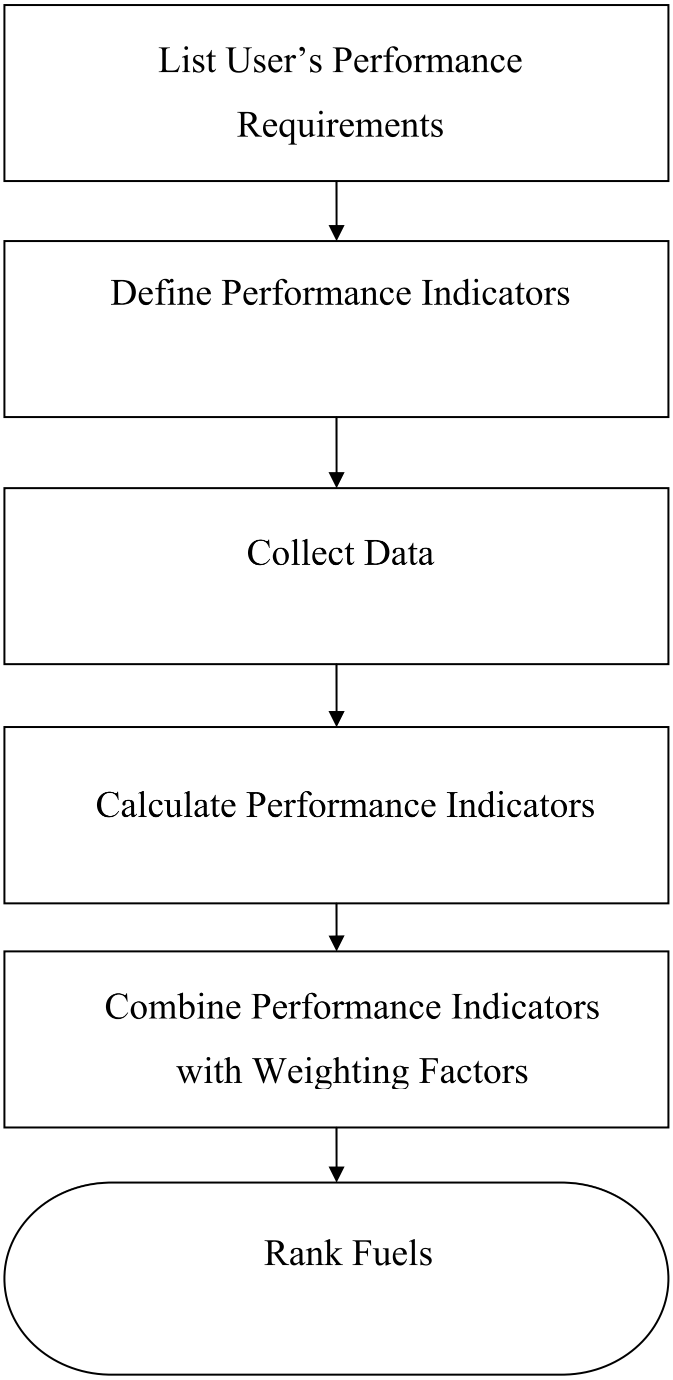


Figure 3.1: Ranking Flow Chart

The first step, listing user's performance requirements, should be performed via clear communication between the engineer and the user. The result of the ranking process will only be beneficial to the user if requirements established accurately outline the user's needs. The user identifies needs through performance requirements, which are non-technical criteria. An example of a performance requirement is the minimization of combustion equipment cleaning. Further details on listing performance requirements are given in section 3.2.

The second step, defining performance indicators, provides the connection between users' non-technical requirements and data. For each requirement a performance indicator is defined which uses data to address the user's concern. To make technical performance indicators easy to understand a functional unit of one year's energy demand is selected. An example performance indicator for the case of required minimal equipment cleaning would be the mass of ash accumulated per year. Some common performance indicators are defined in section 3.3.

The third step is collecting data for each possible fuel. The data required will be dictated by the performance indicators defined. For example, if a user requires minimized combustion equipment cleaning and the annual mass of fuel ash is defined as a performance indicator then fuel ash content becomes important data. Depending on individual circumstances data is obtained from literature or evaluated experimentally. Fuel property and emission factor data is discussed in section 3.4.

The fourth step is calculating performance indicators. This step is performed by substituting data collected in the third step into indicator definitions which are developed in the second step. Section 3.5 explains the calculation of performance indicators.

The fifth and final step is the combination of performance indicators with weighting factors. The result of this step is the assignment of a single numerical score to each fuel. Scores for different fuels can be used to rank the list of fuels from most to least suitable. The combination of performance indicators with weighting factors is discussed in section 3.6.

3.2 Listing Performance Requirements

3.2.1 Introduction

Biofuel users determine their level of satisfaction with a given fuel on the basis of numerous criteria, which are given the label “performance requirements” within this thesis. Figure 3.2 shows a list of performance requirements which will apply to many biomass fuel users. These requirements are explained in farther detail in this section. Some users may also have unique requirements not listed here. It is the responsibility of the engineer applying the tool to establish a complete list of performance requirements for each individual user. The importance of clear communication with the user about his or her requirements cannot be overstated.

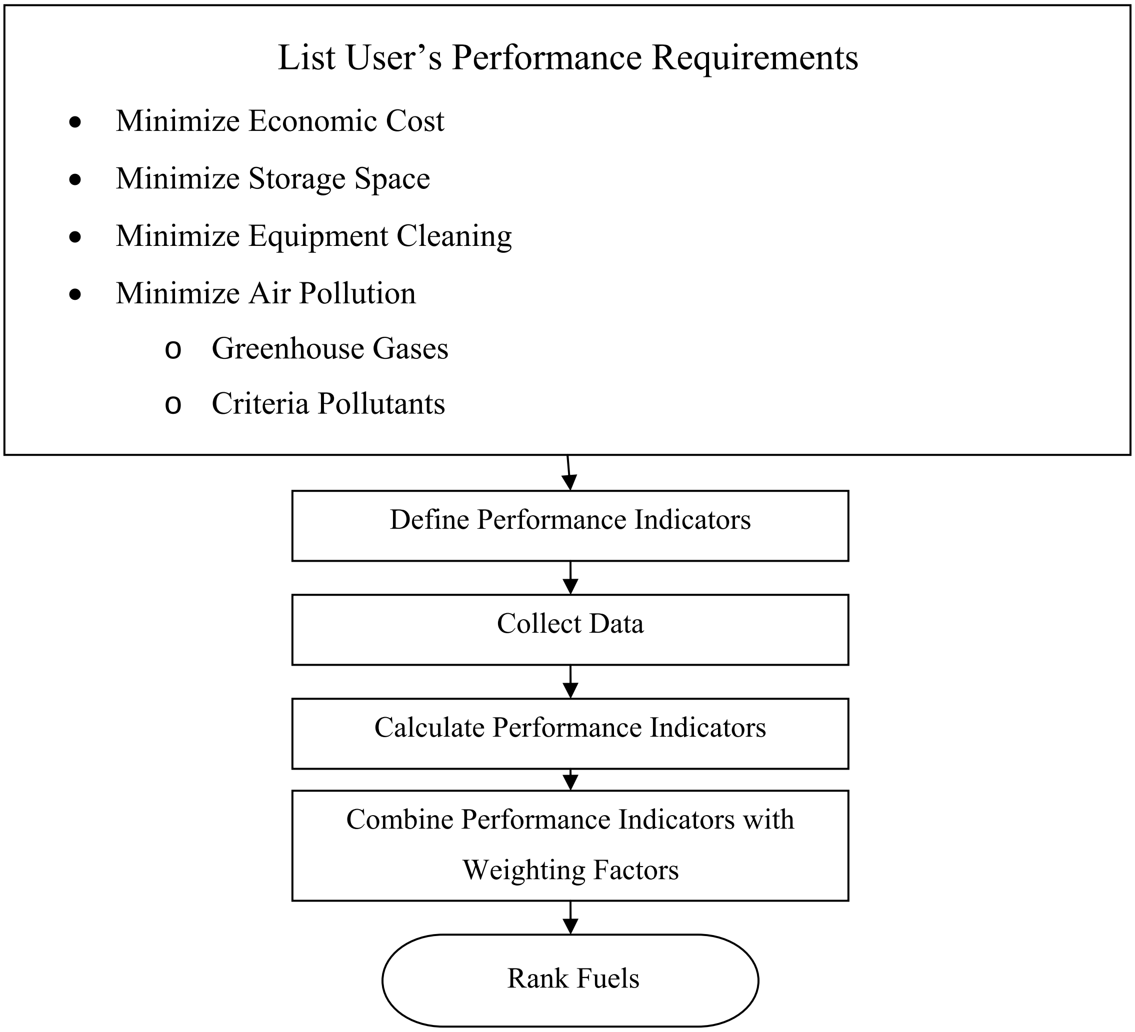


Figure 3.2: Listing Requirements Example

3.2.2 Cost

A typical performance requirement is minimized economic cost of satisfying energy demand. Recall that this decision tool is designed for users with existing combustion equipment and that within the scope of this thesis equipment costs are not considered. The total cost associated with biomass fuel can be broken down and related to fuel life cycle stages. It is desirable to minimize the total cost paid by the user.

3.2.3 Space

Another common performance requirement is minimized fuel storage space. This single performance requirement addresses two user concerns; the size of space allocated to fuel storage and the number of times per year which the space must be refilled. Biomass harvest seasons are often non-concurrent with high energy demand seasons so biomass fuel is often stored for a number of months between harvest and combustion (Tripathi, Iyer and Kandpal 1998).

3.2.4 Cleaning

A third common performance requirement is minimized equipment cleaning. All combustion equipment should be kept clean to allow consistent operation. Clean equipment supports designed air flow and thus reduces the emission of carbon monoxide and unburned hydrocarbons (Kristensen and Kristensen 2004). Reduction of these emissions supports efficient combustion (Tillman 1991). Cleaning of small scale biomass appliances is considered a nuisance because of the time and effort required. In industrial settings equipment cleaning requires labor and perhaps undesired equipment down time.

3.2.5 Emissions

Another common requirement is minimized air pollution. Some users want to minimize air pollution because of their own environmental concerns. This is the case with many small scale users. Users with industrial systems require their emissions to comply with legislation to avoid fines and maintain a positive public image.

Common air pollutants to minimize include five EPA criteria pollutants – volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter, and sulfur oxides (Winebrake, Corbett and Meyer 2007). Many users are also concerned with greenhouse gas emissions. Three frequently monitored greenhouse gases are carbon dioxide, methane, and nitrous oxide (Petersen and

Kristin 2006). Users may be interested in any combination of these pollutants or other pollutants not listed here.

3.2.6 Conclusion

A complete list of performance requirements which accurately represent the criteria the user judges a fuel by must be established during the first step of the ranking process. The engineer applying the ranking tool must communicate effectively with the user to establish this list of performance requirements. Subsequent ranking tool steps are discussed below.

3.3 Defining Performance Indicators

3.3.1 Introduction

After establishing a list of requirements through communication with the user the engineer should develop corresponding performance indicators. This process is represented in Figure 3.3: Example Performance Indicators. For each indicator an equation is developed which can be used to calculate the indicator using data which will be collected as described in section 3.4.

Indicators for the requirements described in section 3.2 are developed in this section. The addition of performance requirements not discussed in this thesis will require additional indicators. It is the responsibility of the engineer to define performance indicators.

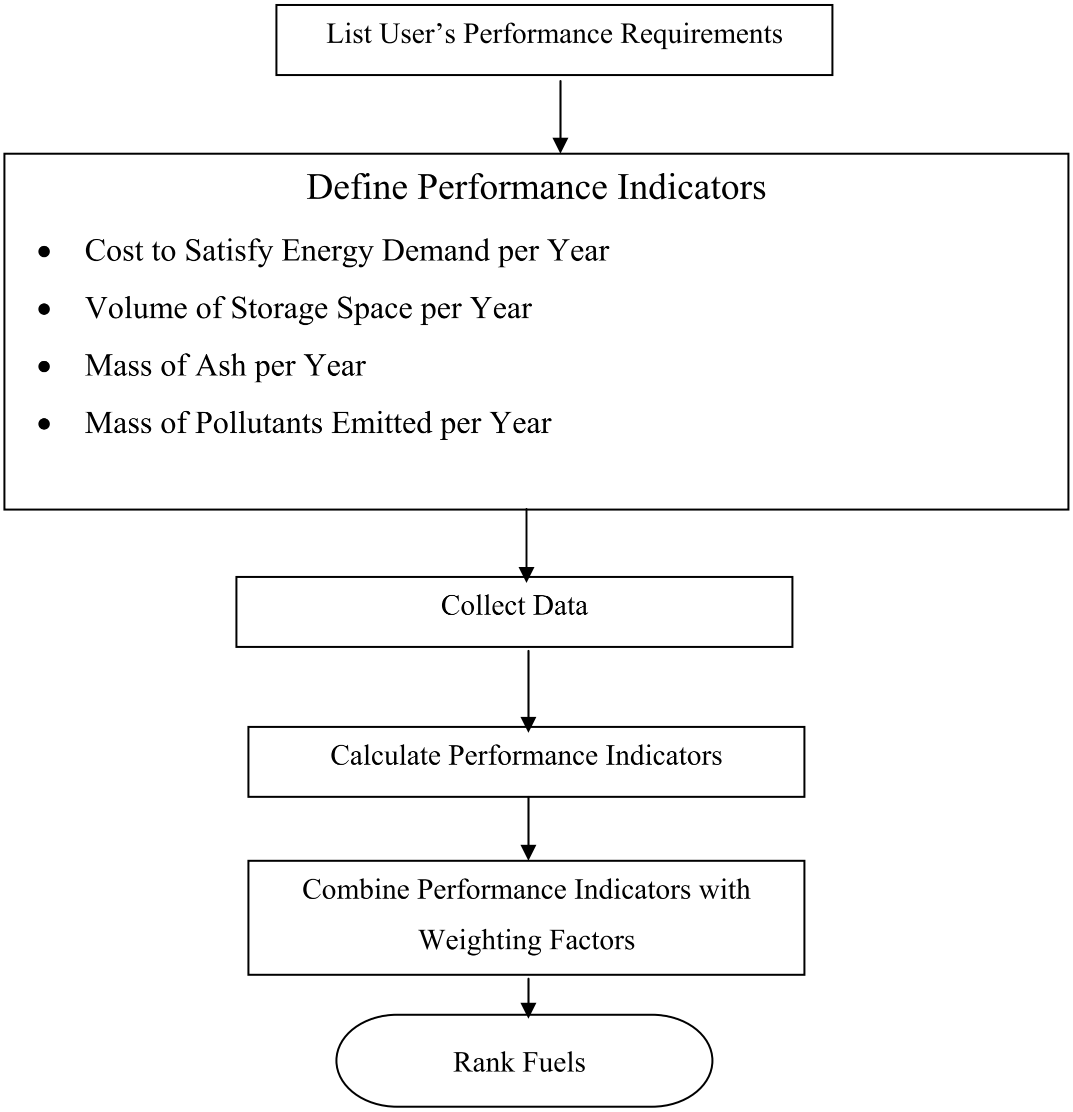


Figure 3.3: Performance Indicators Example

A functional unit of one year's energy supply is used to make extrinsic indicators easily understood. Annual energy demand can be estimated by inquiring about the user's past fuel consumption, although more complex models can be developed to estimate energy needs(Moran and Shapiro). Please note that properties introduced in this section are explained in more detail in section 3.4.

3.3.2 Cost

The first performance indicator defined is the total cost of satisfying energy demand for one year, I_{econ}. This indicator is defined in Equation 3.1. Equations 3.1 through 3.5 are the original work of the thesis' author.

$$I_{econ} = \frac{E_a C_{flc}}{HV \eta_{TH}} \qquad \textbf{Equation 3.1}$$

I_{econ} has units of dollars per year. E_a, energy demand, has an energy unit per year such as MJ/year. HV, heating value, has units of energy per unit mass such as MJ/kg The heating value should be the higher heating value (HHV) for exhaust gas condensing equipment and the lower heating value (LHV) for equipment with an exhaust temperature above the boiling point of water (Sheng and Azevedo 2005). η_{TH}, the thermal efficiency, is a unitless number between zero and one. C_{flc} is the fuel cost to the user over its life cycle per unit mass and has units such as dollars/kg. C_{flc} is calculated using Equation 3.2 and includes purchasing delivered fuel, operating combustion equipment, and disposing of ash.

$$C_{flc} = \frac{E_a}{HV \times \eta_{TH}} [C_{df} + C_{ashd} a(1-w) + C_{op} HV \eta_{TH}] \quad \textbf{Equation 3.2}$$

C_{df} is the cost per unit mass which the user pays for delivered fuel. C_{ashd} is the unit mass cost of ash disposal. This cost will often apply to industrial users who generate large masses of ash. Home biomass users can often dispose of ash in their household garbage without cost. Fuel moisture content, w, is evaluated on a wet basis. Fuel ash content, a, is evaluated on a moisture free basis. C_{op} is the operating cost of combustion equipment per net unit energy. When air pollution control equipment is in place, as in many larger systems, C_{op} should include the cost of operating this equipment. Industrial users may also have additional costs they wish to account for including non-technical items such as public image and safety.

3.3.3 Space

The second performance indicator is the volume of storage space required for a year's fuel supply, I_s. This indicator addresses the performance requirement of minimized storage space. This indicator is calculated using Equation 3.3, shown below.

$$I_s = \frac{E_a}{HV \eta_{TH} d_b} \qquad \textbf{Equation 3.3}$$

Fuel bulk density, d_b, has units of mass per volume such as kg/m^3. The units for the space indicator will be volume, such as m^3, per year

3.3.4 Cleaning

The third performance indicator is the mass of ash in an annual fuel supply, I_{cl}. This addresses the requirement from the cleaning category. This indicator is calculated using Equation 3.4, shown below and has units such as kg/year.

$$I_{cl} = \frac{E_a a(1-w)}{HV\eta_{TH}} \qquad \textbf{Equation 3.4}$$

3.3.5 Emissions

The remaining indicators address air pollution requirements. The number of air pollution indicators will be equal to the number of pollutants the user has interest in. Equation 3.5 is applied separately to each pollutant of interest.

$$I_{envi} = \frac{E_a F_i}{\eta_{TH}} \qquad \textbf{Equation 3.5}$$

I_{envi} is the mass of the ith pollutant emitted per year. F_i, the emissions factor for the ith pollutant, has units of mass of pollutant per unit fuel heating value. For example, an emission factor of 500 mgCO/MJ would mean that when fuel with a heating value of 1 MJ is burned under typical conditions 500 mg of carbon monoxide is emitted.

3.3.6 Conclusion

Common performance requirements and corresponding indicators are summarized in Table 3.1: Example Performance Requirements and Indicators which appears below:

Requirement	Indicator
Minimize Energy Cost	I_{econ}, Life Cost of Fuel (Dollars/year)
Minimize Fuel Storage Space	I_s, Volume of Fuel (m^3/year)
Minimize Equipment Cleaning	I_{cl}, Ash from Fuel (kg/year)
Minimize Air Pollution	I_{env}, Mass of Air Pollutants Emitted (kg/year)

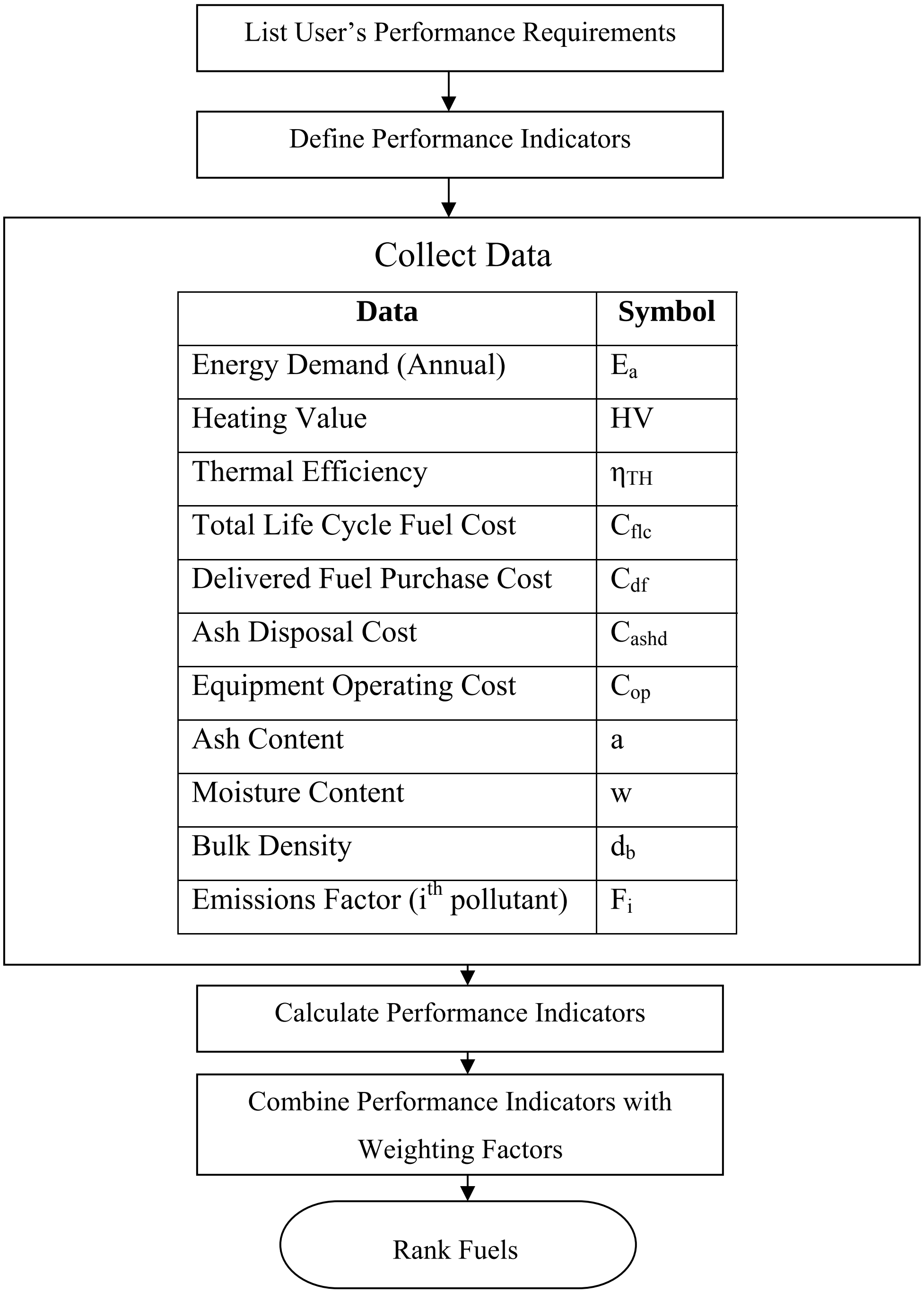
Table 3.1: Example Performance Requirements and Indicators

3.4 Collecting Data

3.4.1 Introduction

The third step in the ranking process is collecting data. Data will typically include a selection of fuel properties as well as emissions factors and thermal efficiencies. Data may be obtained from literature or experimentally. Data should only be taken from literature if similar equipment and fuels are being used under similar conditions.

The data required is a function of the performance requirements being addressed. Below is a discussion of data required to calculate the performance indicators discussed in section 3.3. The addition of new performance indicators may create a need for additional data. Data and symbols are listed in Figure 3.4: Example Data Collection. Sample data is presented in Tables 3.2 through 3.7 and discussed throughout section 3.4. Note that data provided in these tables is only intended to provide readers with a sense of typical estimates of fuel properties. Readers should be aware that property values can vary significantly.



Data	Symbol
Energy Demand (Annual)	E_a
Heating Value	HV
Thermal Efficiency	η_{TH}
Total Life Cycle Fuel Cost	C_{flc}
Delivered Fuel Purchase Cost	C_{df}
Ash Disposal Cost	C_{ashd}
Equipment Operating Cost	C_{op}
Ash Content	a
Moisture Content	w
Bulk Density	d_b
Emissions Factor (i^{th} pollutant)	F_i

Figure 3.4: Example Data Collection

3.4.2 Costs

When users wish to minimize cost fuel prices (including delivery) per unit mass, C_{df}, must be known. Biomass fuels can be sold by mass although sales by volume and count also occur. Prices may also be set using methods which account for heating value. Prices of many fuels depend on quantities purchased as well as market demand. Therefore, it is best to obtain current prices from vendors who the user may actually purchase from. General prices applicable at all times in all regions are virtually nonexistent.

The cost of ash disposal per unit mass, C_{ashd}, is also required. This price will fluctuate with location. Occasionally ash from large industrial systems is sought out by woodlot managers to be used for forest soil enhancement (Mahendrappa et al. 2006; Wikström 2007). In these cases the cost of ash disposal may be negative if ash can be sold. In some locations ash disposal is government regulated and disposal cost will be dependent on proximity to the nearest approved disposal site, as transportation of ash will represent a flexible cost.

Equipment operating cost per net unit energy, C_{op}, is also required. This includes electric costs for running pumps, fans, and other electrical components. Industrial users may also calculate equipment maintenance costs and employee labor costs based on previous experiences.

3.4.3 Heating Values

Heating value, also called calorific value, describes the amount of energy released during combustion of a unit fuel mass. Heating values are reported as higher or lower heating values based on whether the original and generated water in combustion products is in liquid or gaseous form, respectively (Sheng and Azevedo 2005). For biomass combustion appliances with exhaust gas temperatures below the boiling point of water the higher heating value represents the maximum energy available. The lower heating value represents the energy available to devices with higher exhaust temperatures. The construction of non-condensing combustion equipment is simpler and cheaper.

As this non-condensing equipment is more common it is often the lower heating value of fuel which must be obtained.

Heating values may be measured for a biomass sample using a bomb calorimeter. Equations have also been proposed to predict heating values from proximate, ultimate, and chemical analysis data (Sheng and Azevedo 2005). Higher or lower heating values for many materials may be obtained from literature. Examples of heating values are shown below in

Table 3.2: Heating Values of Biomass Fuels.

Biomass Fuel	**LHV (MJ/kg)**	**HHV (MJ/kg)**	**(Ref)**
Commercial Wood Pellet	19.0	20.3	(Obernberger and Thek 2004)
Straw Pellet	17.4	18.6	(Obernberger and Thek 2004)
Cotton Gin Waste Pellet		18.3	(Holt, Blodgett and Nakayama 2006)
Tomato Pellet		22.7	(Holt, Blodgett and Nakayama 2006)
Cardoon Pellet		14.8	(Holt, Blodgett and Nakayama 2006)
Olive Stone		19.4	(Holt, Blodgett and Nakayama 2006)
Hazelnut Shell		19.0	(Koyuncu and Pinar 2007)
Peanut Shell		15.3	(Koyuncu and Pinar 2007)
Corncob (Kernels Removed)		12.45	(Koyuncu and Pinar 2007)
Rice Husk Briquette		16.0	(Kim et al. 2005)
Switchgrass		17.5	(Bridgeman et al. 2007)
Bagasse		16.9	(Turn et al. 2006)
Wheat Straw		14.9	(Koyuncu and Pinar 2007)
Straw Cattle Bedding		11.5	(Koyuncu and Pinar 2007)
Birch Wood		16.9	(Sippula et al. 2007)
Birch Bark		23.6	(Sippula et al. 2007)
Spruce Wood Chips (10% Moisture)		16.4	(Strehler 2000)
Spruce Logs (40% Moisture)		10.1	(Strehler 2000)
Pine Stem Wood	17.6		(Sippula et al. 2007)

Biomass Fuel	LHV (MJ/kg)	HHV (MJ/kg)	(Ref)
Pine Bark	18.2		(Sippula et al. 2007)
Charcoal		19.3	(Koyuncu and Pinar 2007)

Table 3.2: Heating Values of Biomass Fuels

3.4.4 Thermal Efficiencies

Thermal efficiency, η_{TH}, appears in the definitions of all performance indicators discussed above. Within this thesis thermal efficiency is defined as the ratio of useful energy delivered to heating value of fuel consumed. Useful energy delivered would be either space or process heat, or electrical energy in the case of generating systems. For example, in the case of a wood chip fired district heating system the thermal efficiency would be the ratio of space heat delivered to system customers to heating value of wood chips consumed.

In some cases thermal efficiency has been shown to depend more on equipment than fuel selection (Kristensen and Kristensen 2004; González et al. 2004). In other cases ranges of efficiencies have been measured on single pieces of equipment firing different fuels (González et al. 2006; Turn et al. 2006).

Inefficiencies include incomplete combustion as well as losses due to stack gas temperatures exceeding inlet air temperatures. Steam cycle generated electricity typically has large losses associated with the condensing stage of the cycle (Moran and Shapiro, 2000).

Evaluating thermal efficiency is often difficult but some estimates may be found in literature. Table 3.3: Bioenergy System Thermal Efficiencies presents a few examples. A procedure used to measure thermal efficiency is outlined and exemplified in Chapter 4. If thermal efficiency data is collected from literature it is necessary to verify that the authors were operating similar equipment on similar fuels under similar conditions. Otherwise, published data will not be applicable.

Biomass Fuel	Combustion Appliance	Efficiency %	(Ref)
Wood	Simple Heating Stove	46	(Koyuncu and Pinar 2007)
Charcoal	Simple Heating Stove	46	(Koyuncu and Pinar 2007)
Loose Straw	25 kW Sawdust Boiler	73	(Collura et al. 2006)
Straw Pellet	25 kW Sawdust Boiler	84	(Collura et al. 2006)
Baled Straw	50-500 kW Boilers (various)	75-87	(Kristensen and Kristensen 2004)

Table 3.3: Bioenergy System Thermal Efficiencies

3.4.5 Bulk Densities

Bulk density is the average density within a container of material, accounting for both material and airspace. It is measured by massing a known volume of fuel. Estimates for bulk densities may be found in literature and actual measurements are often quick and simple (Mani, Tabil and Sokhansanj 2006). Some bulk densities are given in Table 3.4: Biomass Bulk Densities. When bulk density data is found in literature moisture content should be verified, as moisture can sometimes account for half the mass of a given volume of biomass. With the exception of the two pellet types and the 10% moisture wood chips, all data in Table 4.3 represents naturally wet biomass.

Biomass Fuel	Bulk Density (kg/m^3)	(Ref)
Loose Straw	40	(Mani, Tabil and Sokhansanj 2006)
Straw Pellets	660	(Obernberger and Thek 2004)
Sawdust	180	(Strehler 2000)
Loose Wood Residue	250	(Mani, Tabil and Sokhansanj 2006)
Spruce Wood Chips (40% moisture)	215	(Strehler 2000)
Spruce Wood Chips (10% moisture)	160	(Strehler 2000)
50 cm Wood Logs (not piled)	250	(Strehler 2000)
50 cm Wood Logs (Neatly Piled)	500	(Strehler 2000)

Biomass Fuel	Bulk Density (kg/m^3)	(Ref)
Wood Pellets	591	(Mani, Tabil and Sokhansanj 2006)

Table 3.4: Biomass Bulk Densities

3.4.6 Ash Contents

Ash content is the ratio between mass of incombustible ash to total dry mass. It is important to realize that fuel ash contents are usually reported on a moisture free basis (Erlich et al. 2006). This convention has a large impact on the mass of ash which is calculated to be in fuel. Ash content can be evaluated by massing a dried fuel sample and applying an intense source of heat until the sample mass remains constant. Estimates of ash contents for some materials are found in literature. Table 3.5: Biomass Ash Contents lists ash contents of some biomass fuels. Ash contents can be increased by handling methods, especially those which involve biomass resting on uncovered soil. This can explain why straw cattle bedding has a higher ash content than the other materials in Table 3.5.

Biomass Fuel	Ash Content (% dry mass)	(Ref)
Wheat Straw	8.3	(Mani, Tabil and Sokhansanj 2006)
Corn Stover	7.5	(Mani, Tabil and Sokhansanj 2006)
Switchgrass	5.5	(Mani, Tabil and Sokhansanj 2006)
Reed Canary Grass	6.0	(Bridgeman et al. 2007)
Straw Cattle Bedding	20.1	(Koyuncu and Pinar 2007)
Peanut Shell	2.2	(Koyuncu and Pinar 2007)
Charcoal	5.9	(Koyuncu and Pinar 2007)
Bark (non-species specific)	3.5	(Wikström 2007)
Sawdust (non-species specific)	0.5	(Wikström 2007)
Premium Wood Pellets	0.5	(Obernberger and Thek 2004)

Table 3.5: Biomass Ash Contents

3.4.7 Moisture Contents

Moisture content is another property required for a variety of performance indicators. This is defined as the ratio of water mass to total wet mass. Moisture content is calculated by dividing the loss of mass during a drying process by the original mass. Biomass is often dried at temperatures a few degrees above 100 °C for several hours until the material achieves a constant mass.

Table 3.6: Biomass Moisture Contents provides some published data. If selecting published moisture content data verify that material sources, handling, and storage methods were similar.

Biomass Fuel	**Moisture Content (% wet)**	**(Ref)**
Wheat Straw	8.3	(Mani, Tabil and Sokhansanj 2006)
Corn Stover	6.2	(Mani, Tabil and Sokhansanj 2006)
Switchgrass	5.2	(Mani, Tabil and Sokhansanj 2006)
Bagasse	12.4	(Turn et al. 2006)
Bark (non-species specific)	55	(Wikström 2007)
Fresh Pine and Spruce Forest Residue	60	(Wihersaari 2005a)
Naturally Dried Pine and Spruce Forest Residue	40	(Wihersaari 2005a)
Premium Wood Pellets	5.2	(Holt, Blodgett and Nakayama 2006)
Charcoal	4.1	(Koyuncu and Pinar 2007)
Cotton Gin Waste Pellets	8.3	(Holt, Blodgett and Nakayama 2006)

Table 3.6: Biomass Moisture Contents

3.4.8 Emission Factors

Emission factors are important when users specify air pollution requirements. An emission factor gives the mass of a pollutant typically emitted when fuel with a unit heating value is burned. These factors may be measured or may be available in literature for some situations. Emissions factors from literature are only applicable when combustion equipment, fuels, and operating conditions are very similar. Air pollutant formation is complex and estimates may differ from actual releases due to issues including inconsistent fuel quality, equipment malfunctions, and operator error.
Table 3.7: Biomass Emissions Factors shows some sample emission factors for certain fuels and systems. Blank spaces in Table 3.7 are intended and indicate that data was not available in references.

Fuel	System	CO	NO_x	SO_2	NO	NO_2	PM	(Ref)
Hazelnut Shell	Space Heating Stove	1667	5.65	20.52				(Koyuncu and Pinar 2007)
Walnut Shell	Space Heating Stove	2445	8.78	31.65				(Koyuncu and Pinar 2007)
Peanut Shell	Space Heating Stove	2422	18.32	37.72				(Koyuncu and Pinar 2007)
Corncob (Kernels Removed)	Space Heating Stove	3276	0.75	3.75				(Koyuncu and Pinar 2007)
Straw Cattle Bedding	Space Heating Stove	12490	59	114				(Koyuncu and Pinar 2007)
Charcoal	Space Heating Stove	2095	2.62	0				(Koyuncu and Pinar 2007)
Cotton Gin Waste Pellets	Top Fed Pellet Stove	10180		264	1200	13	2170	(Holt, Blodgett and Nakayama 2006)
Wood Pellets	Top Fed Pellet Stove	1140		70	510	1140	440	(Holt, Blodgett and Nakayama 2006)

Table 3.7: Biomass Emissions Factors

(All Emission Factors in mg/MJ)

3.5 Calculating Performance Indicators

After performance indicators have been defined and data has been collected the actual indicator values are calculated. These calculations involve merely substituting data into previously developed Equations. Spreadsheets are often helpful in this step since each indicator calculation must be performed for each fuel. Figure 3.5: Example Indicator Calculations shows where this process fits in the overall ranking algorithm.

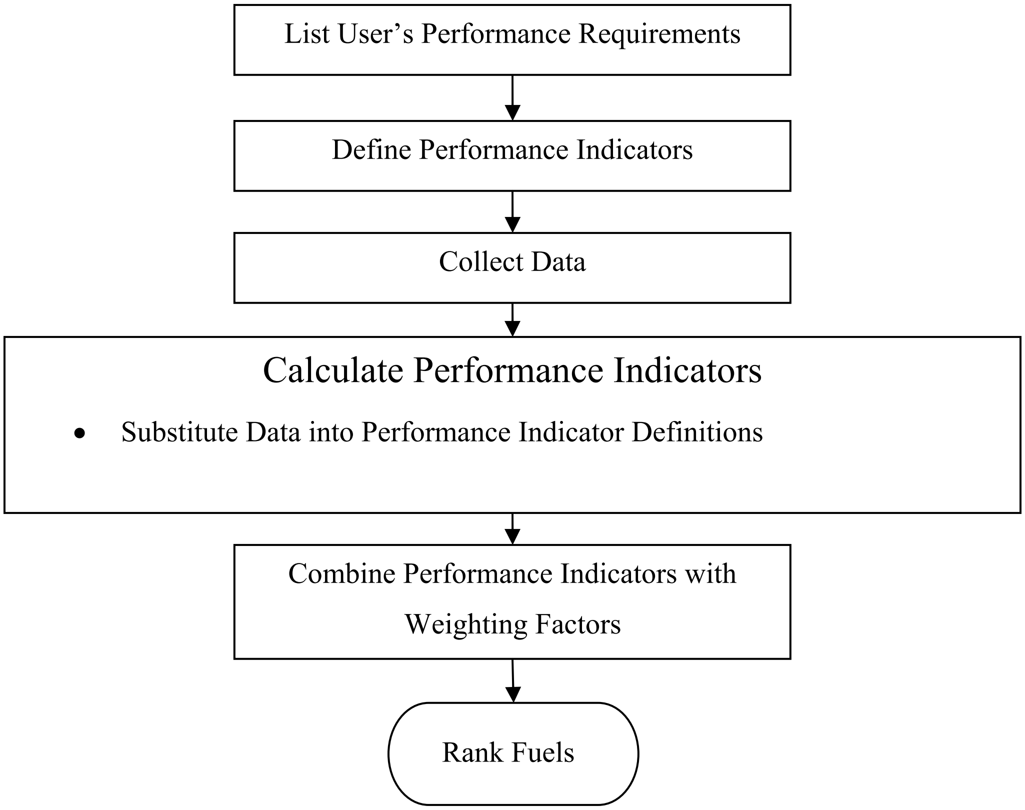


Figure 3.5: Example Indicator Calculations

3.6 Combining Indicators with Weighting Factors

3.6.1 Introduction

After performance indicators have been calculated, as discussed in section 3.5, they are combined using weighting factors. The final result of this fifth step is the assignment of a single numerical score to each fuel. These scores allow fuels to be ranked according to their ability to satisfy the performance requirements which the user identified in the initial step of the ranking process. There are two sub-steps in this fifth and final process. These are shown in
Figure 3.6: Combining Indicators Example.

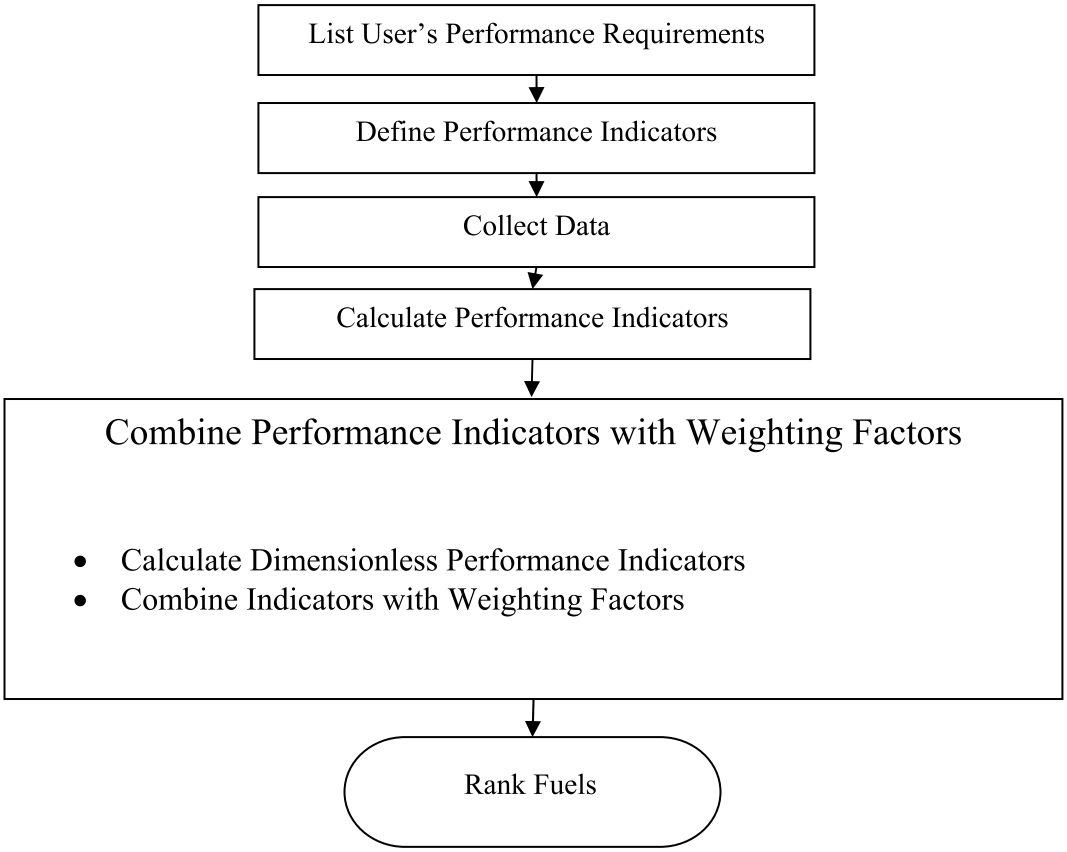


Figure 3.6: Combining Indicators Example

3.6.2 Calculate Dimensionless Performance Indicators

To allow indicators for different requirements to be related all indicators are converted to dimensionless form. For each performance indicator the maximum and minimum values are identified from the list of fuels. Next, all indicators for each fuel are converted to dimensionless form using Equation 3.6. Equation 3.6 is sourced from (Zhou, Jiang, Quin, 2007) and was selected for this thesis because it is simple to apply and ensures the same range of dimensionless indicators for all categories. While this may seem to be a weakness of this ranking tool (the range of dimensionless indicators will be from 0 to 1 regardless of the range of dimensional indicators) it is actually appropriate to use an equal dimensionless range for all categories so that the category weighting factors, discussed in the next section, have their true intended effect on the outcome of the ranking tool.

$$I_{Nji} = \frac{I_{j\max} - I_{ji}}{I_{j\max} - I_{j\min}} \qquad \textbf{Equation 3.6}$$

I_{Nji} is the dimensionless indicator for the i^{th} fuel in the j^{th} performance category. I_{jmax} and I_{jmin} are the maximum and minimum values of the j^{th} performance indicator, and I_{ji} is the j^{th} performance indicator for the i^{th} fuel. A full example application of the ranking tool, including calculation of dimensionless performance indicators, is found in section 3.7.

For the performance indicators discussed in this thesis the goal is always minimizing the indicator (for example, minimizing storage volume). However, in terms of dimensionless indicators the goal of minimization and maximization is reversed, so that a fuel which requires the least storage space will actually have the highest dimensionless storage indicator. The ranking tool should only be used with performance indicators which are desirable to minimize, such as those discussed above (cost, storage volume, and others).

3.6.3 Combining Indicators with Weighting Factors

The final step in the calculation process - the combination of multiple indicators into a single indicator - is performed by applying Equation 3.7. The numerator of Equation 3.7 was previously published by Zhou, Jiang, and Qin using different nomenclature (Zhou, Jiang and Qin 2007). The denominator of Equation 3.7 is discussed below.

$$I_{si} = \frac{\sum_{j=1}^{n} w_j I_{Nji}}{\sum_{j=1}^{n} w_j} \times 100\%$$

Equation 3.7

I_{si} is the single indicator for the i^th^ fuel, and n is the number of performance indicators. The weighting factor for the j^th^ performance requirement is w_j.

For ease of understanding the single indicators are presented as a percentage of the maximum possible indicator. The maximum indicator (100%) would be assigned to a fuel which outperforms all other fuels in every category, making it the reasonable best choice. Fuels with higher scores better suit the requirements of the user. A score of 0% would indicate that a fuel was outperformed by all other fuels with regard to all requirements. This presentation of each fuel's score as a percentage of the maximum possible score is achieved by the denominator of Equation 3.7, which was added to the numerator of that Equation by this thesis' author for this purpose.

Equation 3.7 is applied to each fuel on the user's option list. It is important to realize that weighting factors have a large impact on the fuel rankings. Weighting factors must be selected using effective communication between the engineer and the user, in the same way performance requirements are established. It is convenient to establish weighting factors at the same time as requirements, although it can also be done any time before Equation 3.7 is applied by the engineer.

Weighting factors allow the user to give performance categories different levels of importance and impact on final fuel rankings. This addresses the issue that different users place different values on each performance requirement. For example, suppose a user requires minimal fuel cost and equipment cleaning but feels that cost is three times more important than cleaning. The cleaning weighting factor, $w_{cleaning}$, will have a value of 1 and w_{cost} a value of 3.

3.7 Decision Tool Example

This section includes an example application of the Biomass Fuel Ranking tool. This fictitious example is the original work of this thesis' author. Although the fuel property data is fictitious, the values chosen are within the same orders of magnitude as the previously published data presented in Tables 3.2 through 3.7.

3.7.1 Introduction

Suppose a homeowner heats a portion of their home with a pellet stove. The stove has been designed with multi fuel capability and three suitable pellet types are available for purchase. The pellet types are wood, wheat straw, and switchgrass. The user has an annual energy demand for 50 000MJ of space heat. Throughout section 3.7 we apply the decision tool to this situation to rank the three fuel options according to how well each satisfies the user's needs.

3.7.2 Step 1: List Performance Requirements

Suppose the user identifies the following performance requirements: minimize economic cost of supplying energy, minimize equipment cleaning, minimize fuel storage space, and minimize air pollution. The user has interest in three air pollutants. These are particulate matter, because of staining on the user's house near exhaust venting, carbon monoxide, because of human health concerns, and sulfur dioxide because of good environmental stewardship – specifically concerns over acid rain. In addition to these requirements (which were all discussed in previous sections) the user also has a unique requirement: they prefer to buy products produced locally because of a personal preference for generating local employment. To summarize, the list of performance requirements is:

- Minimize Cost
- Minimize Storage Space
- Minimize Cleaning
- Minimize Air Pollution, Specifically:
    - Particulate Matter
    - Carbon Monoxide
    - Sulfur Dioxide
- Support Local Business

The relative importance of requirements to the user and appropriate weighting factors are discussed in section 3.7.6.

3.7.3 Step 2: Define Performance Indicators

A suitable list of performance indicators must be developed to address the concerns which the user identified in the first step. The specified 50 000MJ annual energy demand will be used as a functional unit for the indicators which are extrinsic. Performance requirements and corresponding indicators are listed in Table 3.8: Pellet Stove Performance Requirements and Indicators.

Requirement	**Indicator**
Minimize Cost	I_{econ}, Annual Fuel Cost ($)
Minimize Storage Space	I_s, Annual Fuel Volume (m^3)
Minimize Cleaning	I_{cl}, Annual Ash Mass (kg)
Minimize PM	I_{envPM}, Annual Emission (kg)
Minimize CO	I_{envCO}, Annual Emission (kg)
Minimize SO_2	I_{envSO2}, Annual Emission (kg)
Support Local Business	I_{LB}, Distance to Facility (km)

Table 3.8: Pellet Stove Performance Requirements and Indicators

The economic, space, cleaning, and environmental indicators will be calculated using Equations 3.1 through 3.5. The indicator selected for supporting local business is the distance from the user's home to each respective pellet production facility.

3.7.4 Step 3: Collect Data

Suppose the fuel properties are as shown in Table 3.9: Pellet Data. Obtaining this data would signify the completion of the third step in the decision tool application. The lower heating value is used rather than the higher because the user's pellet stove has an exhaust temperature high enough to prevent water from condensing in exhaust gas. The data in Table 3.9 would be available from pellet manufacturers in many cases.

	Wood	**Wheat Straw**	**Switchgrass**
Cost ($/kg)	0.25	0.22	0.20
LHV (MJ/kg)	17.4	16.6	16.8
η_{TH} (%)	90	88	80
d_b (kg/m^3)	650	630	680
w (% wet)	5.8	8.0	6.2
a (% dry)	0.5	8.3	5.5
F_{co} (mgCO/MJ)	1200	1300	1800
F_{PM} (mgPM/MJ)	500	2000	1500
F_{SO2} (mgSO_2/MJ)	110	800	600
I_{LB} (km)	150	500	200

Table 3.9: Pellet Data

3.7.5 Step 4: Calculate Performance Indicators

By applying Equations 3.1 through 3.5 using data in Table 3.9 performance indicators can be calculated for each of the three fuels. These indicators are presented in Table 3.10: Calculated Performance Indicators.

Performance Requirement	**Performance Indicator**	**Wood**	**Wheat Straw**	**Switchgrass**
Minimize Cost	I_{econ}, Annual Fuel Cost ($)	$798.21	$753.01	$744.05
Minimize Storage Space	I_s, Annual Fuel Volume (m^3)	4.91	5.43	5.47
Minimize Cleaning	I_{cl}, Annual Ash Mass (kg)	15.0	261.4	191.9
Minimize PM	I_{envPM}, Annual Emission (kg)	66.7	73.9	112.5
Minimize CO	I_{envCO}, Annual Emission (kg)	27.8	113.6	93.8
Minimize SO_2	I_{envSO2}, Annual Emission (kg)	6.1	45.5	37.5
Support Local Business	I_{LB}, Distance to Facility (km)	150	500	200

Table 3.10: Calculated Performance Indicators

3.7.6 Step 5: Combine Performance Indicators with Weighting Factors

After performance indicators have been calculated they must be converted to dimensionless form using Equation 3.6. A dimensionless indicator of zero identifies the worst fuel with regard to a given requirement while a score of 1 identifies the best with regard to that requirement. Scores between zero and one are proportionally large according to how the fuel performs relative to the other fuels.

Indicator	Wood	Wheat Straw	Switchgrass
I_{Necon}	0.00	0.83	1.00
I_{Ns}	1.00	0.07	0.00
I_{Ncl}	1.00	0.00	0.28
I_{NenvPM}	1.00	0.84	0.00
I_{NenvCO}	1.00	0.00	0.23
$I_{NenvSO2}$	1.00	0.00	0.20
I_{NLB}	1.00	0.00	0.86

Table 3.11: Dimensionless Indicators

After calculating the dimensionless indicators for each fuel, shown above in Table 3.11, weighting factors must be selected before proceeding with the application of Equation 3.7. Suppose the user decides that the space, environmental and local business factors are all of equal importance. The user also decides that the cleaning factor is twice as important as the space factor and that the economic factor is three times as the space factor. This would mean that the weighting factor for economics, w_{econ}, would have a value of 3. w_{env}, w_s, and w_{LB} would each have a value of 1 and w_{cl} would have a value of 2. Equation 3.7 is applied to each fuel separately, resulting in the single overall performance indicators shown in Table 3.12: Single Indicators.

	Wood	Wheat Straw	Switchgrass
Overall Indicator	70.0	34.1	48.6

Table 3.12: Single Indicators

Table 3.12 shows that wood pellets have the highest overall indicator of the three fuels. Therefore, wood pellets are the most suitable of the three fuels for the user's requirements. Switchgrass pellets are the next most suitable fuel, with wheat straw pellets being the least suitable of the three options.

To summarize, the fuel ranking tool has been used to assign a single numerical indicator to each fuel. This allows a clear ranking of the fuels in order from most suitable to least suitable:

1. Wood
2. Switchgrass
3. Wheat Straw

It is important to note that the results given in table 3.12 could change drastically with a change in weighting factors.

Now that the objective of the ranking tool has been realized (a clear ranking of fuels) it is valuable to return to Table 3.10 and verify that the performance of the wood pellets is acceptable to the user. This means that the cost is within budget, the storage space required is available (or at least possible with an acceptable number of fuel storage fillings per season), the ash developed can be cleaned from the equipment with acceptable effort, the emissions are within acceptable limits, and the user is satisfied with the distance from their home to the pellet processing facility.

Chapter 4
Thermal Efficiency Measurement

4.1 Introduction

In order to apply the fuel ranking tool thermal efficiency must be known. As previously mentioned, published thermal efficiency data is available for some specific fuels and systems, such as those in Table 3.3. Published data is only applicable to situations with similar combustion equipment and fuels. Because of these restrictions it is often necessary to measure thermal efficiency. A procedure for measuring thermal efficiency of a biomass combustion device is demonstrated in this Chapter.

In some cases literature reports combustion efficiency rather than thermal efficiency – these two values must not be confused (González et al. 2004; González et al. 2006). Combustion efficiency indicates how much of the heating value is converted to thermal energy. Sources of combustion inefficiency are emissions of carbon monoxide and unburned hydrocarbons (Tillman 1991). Combustion efficiency measurements often involve the concentrations of CO and CO_2 in exhaust gas (González et al. 2004).

Other data required for fuel ranking includes fuel properties and emissions factors. Many fuel properties are available in literature, as shown in the Tables 3.2 and 3.4 through 3.6. Also, many properties (such as bulk density) can be measured quickly using relatively inexpensive equipment (Mani, Tabil and Sokhansanj 2006). Emission factors for a variety of fuels fired in a variety of equipment are also available in literature and examples are given in Table 3.7.

Because thermal efficiency data is not as readily available as other data a possible experimental procedure is presented in this Chapter. Below is a method for evaluating thermal efficiency of a pellet stove.

4.2 Materials and Methods

4.2.1 Introduction

This section contains a discussion of the methods and materials used in this experiment. The pellet stove and fuel are first discussed. Next models for forced and natural convection and radiation heat transfer are developed. Finally, data collection is discussed before moving on to results in section 4.3.

4.2.2 Pellet Stove and Fuel

The efficiency of a commercially available wood pellet stove was measured. According to the stove manufacturer, the stove was designed to use wood pellet fuel conforming to Association of Pellet Fuel Industries (APFI) standards. Properties of APFI premium and standard quality pellets are listed in Table 4.1: APFI Specifications. Fuels not conforming to these specifications may reduce performance or cause the fire in the stove to go out (Canadian Comfort Industries & Dansons Group Inc. 2004a).

Property	**APFI Specification**
Length	Maximum 38.1 mm
Diameter	6 to 9 mm
Density	Minimum 640 kg/m^3
Heating Value	Minimum 19 MJ/kg
Moisture Content	8% Maximum
Ash Content	Premium: 0.75% Maximum Standard: 2.5% Maximum

Table 4.1: APFI Specifications (Canadian Comfort Industries & Dansons Group Inc. 2004a)

The pellet stove is designed and commonly used for space heating. The particular model used is designed to heat areas between 75 and 185 m^2 which require heat inputs of between 4.4 and 14.6 kW. The stove is designed to consume fuel at rates between 0.8 and 2.5 kg/h (Canadian Comfort Industries & Dansons Group Inc. 2004a). A schematic is shown on the following page in Figure 4.1: Pellet Stove Design.

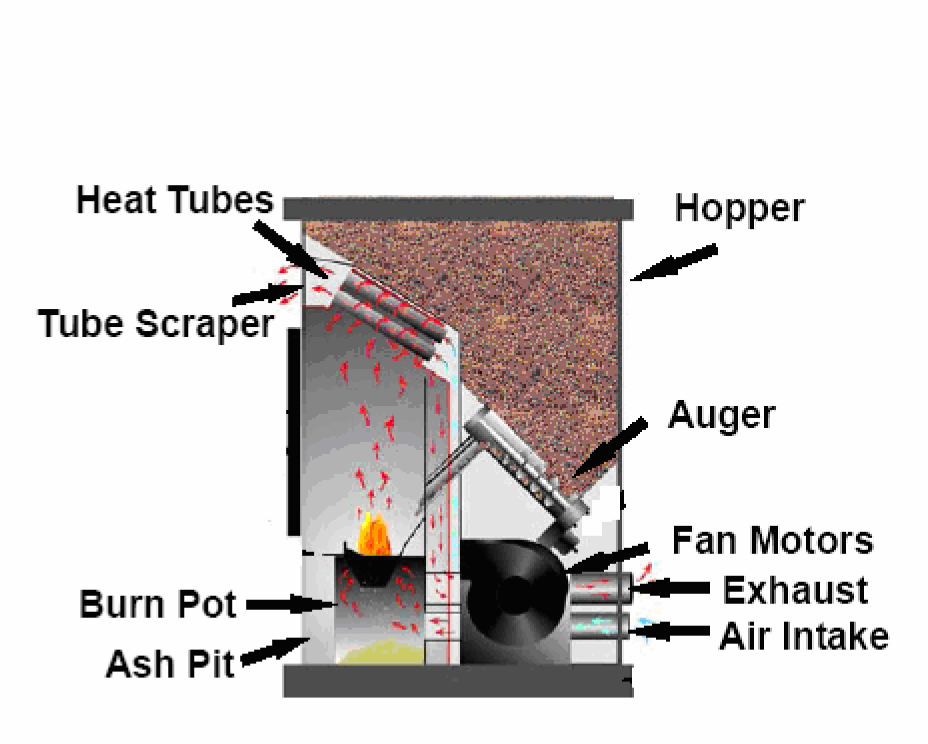


Figure 4.1: Pellet Stove Design (Canadian Comfort Industries & Dansons Group Inc. 2004a)

Fuel is fed from the hopper to the burn pot using the motor driven auger. This process is controlled electronically and users select one of four feed rates. Different feed rates are achieved by varying the idle time between uniform auger operation cycles.

Combustion air is drawn in at the rear of the stove through the air intake. During the first minutes of operation fuel is ignited in the burn pot by a 300 W electric heating element (Canadian Comfort Industries & Dansons Group Inc. 2004a). Combustion air is blown through the bottom of the burn pot by a fan. The flow of air through the burn pot is intended to blow ash into the ash pit. Combustion gases rise and pass over the outside of the Heat Tubes. Combustion gases exit at the rear of the stove and are vented to the atmosphere through 3 inch diameter PL vent pipe.

Room air is drawn in using a second fan and blown through the heat exchanger tubes which discharge at the front of the stove. This second circulation fan operates at any of five fixed speeds. A tube scraper is used to remove ash from the heat tubes. This increases heat exchange efficiency between combustion gases and circulation air. Some specifications of the stove are listed in Table 4.2: Stove Specifications.

Designed Heat Output	4.4 – 14.6 kW
Designed Space Heating Ability	74 – 186 m^2
Electrical Input (normal operation)	175 W
Electrical Input (ignition)	475 W
Designed Fuel Feed Rate	0.8 – 2.5 kg/h
Designed Excess Air Ratio	35
Exhaust Vent	3 inch PL vent

Table 4.2: Stove Specifications (Canadian Comfort Industries & Dansons Group Inc. 2004a)

This pellet stove is exempt from US EPA Phase II requirements because of the designed combustion air supply ratio. Any pellet appliance with a designed excess air ratio of 35 or greater is exempt from EPA regulations (Canadian Comfort Industries & Dansons Group Inc. 2004b).

The pellet stove was installed in the laboratory following the manufacturer’s recommendations for a normal residential installation (Canadian Comfort Industries & Dansons Group Inc. 2004b). The vent pipe configurations was as shown in Figure 4.2: Stove Installation.

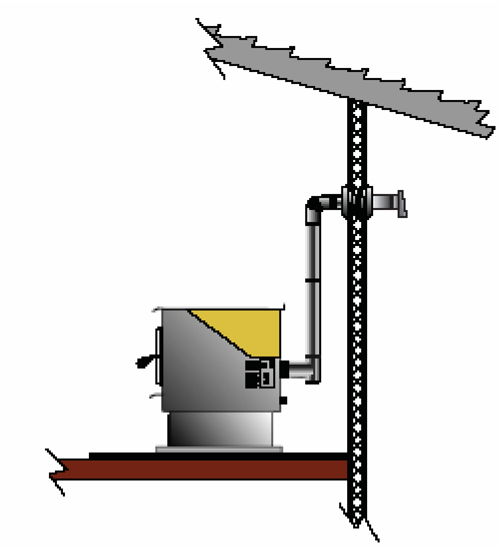


Figure 4.2: Stove Installation (Canadian Comfort Industries & Dansons Group Inc. 2004b)

The efficiency of the pellet stove was evaluated for a specific set of conditions. These conditions were as follows. The highest fuel feed rate and circulation fan speed were selected. The stove was allowed to reach a steady operating condition before data for the efficiency calculation was collected. The steady condition was indicated by constant temperatures at points within the system. The two fuels tested were premium wood pellets and wheat straw pellets.

4.2.3 Thermal Efficiency Model

The thermal efficiency of the pellet stove (η_p) is defined as the ratio of space heat transferred to the room (Q_{sh}) to energy contained in fuel consumed (the product of the lower heating value, LHV, and the mass flow rate of fuel consumed, m_f). Equation 4.1 summarizes the definition of thermal efficiency:

$$\eta_p = \frac{Q_{sh}}{LHVm_f}$$ **Equation 4.1**

The lower heating values of wood and straw pellet fuels were taken from literature. The lower heating values were appropriate because, as shown in Table 4.5, exhaust gas temperatures were above the condensation temperature of water.

The fuel mass feed rate, m_f, was measured. For this measurement the stove igniter was electrically disabled and start up controls were overridden. The highest feed rate was selected and pellets were allowed to fall into the burn pot. Once the burn pot was nearly full of pellets the auger was stopped and pellets were removed and massed on a digital balance. As shown by Equation 4.2 the mass flow rate of fuel was determined by dividing the mass of pellets that had fallen, m_p, by the elapsed time, t.

$$m_f = \frac{m_p}{t}$$ **Equation 4.2**

The rate of space heat transfer to the room (Q_{sh}) was modeled by summing three heat flows. These are:

- Forced Convection Heat Transfer
- Natural Convective Heat Transfer
- Radiation Heat Transfer

4.2.4 Forced Convection Heat Transfer

Energy added to room air by the heat exchanger was given the label Forced Convection Heat Transfer (Q_{fc}). Q_{fc} was modeled using the mass flow of air and the inlet and outlet temperatures. The air inlet temperature data came from a thermocouple placed in ambient room air (T_r), approximately 2 meters away from the stove and not in the direct path of the heat exchanger airflow. A ductwork boot was installed covering the outlet of the heat exchanger so that a single airflow stream was established. The temperature of this stream of outlet air (T_x) was determined using a second thermocouple.

The velocity of air flowing through the heat exchange boot was measured using a pitot tube and digital manometer. Plug flow was assumed because of the small pipe diameter, listed in Table 4.3. The air velocity, V_x, was determined from the pitot tube differential pressure, ΔP_x, using Equation 4.3. The air density, ρ_x, was found in literature according to the outlet temperature.

$$V_x = \sqrt{\frac{2\Delta P_x}{\rho_x}}$$ **Equation 4.3**

The mass flow rate of air through the heat exchanger, m_{ax}, was found using Equation 4.4. The area of the duct boot, A_x, was found by measuring the diameter of this round pipe.

$$m_{ax} = V_x A_x \rho_x$$ **Equation 4.4**

The space heat added to the room by forced convection, Q_{fc}, was calculated using Equation 4.5. The values of specific enthalpy for air at the inlet and outlet of the circulation air system, h_r and h_x, are found in literature according to temperatures T_r and T_x.

$$Q_{fc} = m_{ax}(h_x - h_r)$$ **Equation 4.5**

4.2.5 Natural Convection Heat Transfer

Space heat is also transferred through natural convection. This energy, Q_{nc}, is calculated using Equation 4.6. Equation 4.6 considers the hot surface area of the stove, A_s, the temperature of this part of the stove, T_s, the temperature of air in the room, T_r, and the convective heat transfer coefficient, h.

$$Q_{nc} = hA_s(T_s - T_r)$$ **Equation 4.6**

The value of stove surface area used was only the area which obtained a temperature more than twenty degrees higher than the temperature of room air. This eliminated all surfaces other than the sides and front.

The value of surface temperature used in Equation 4.6, T_s, is an average of three temperatures. These are measured on the front and each side of the stove using thermocouples. These surfaces were then modeled as a single vertical plate of uniform temperature T_s. The hot stove surface area, A_s, was calculated based on measurements of the rectangular sides and front of the pellet stove.

Determining the convective heat transfer coefficient, h, was a multi step process and followed the algorithm given in (Çengel, Turner and Cimbala 2008, p840-847). The first step was calculating the air film temperature, T_f. This was achieved using Equation 4.7. Equations 5.7 through 4.10 were sourced from (Çengel, Turner and Cimbala 2008, p840-847).

$$T_f = \frac{T_s + T_r}{2} \qquad \textbf{Equation 4.7}$$

Once the film temperature had been found some properties of air were found in literature (Çengel, Turner and Cimbala 2008, p987-1030). These properties were: kinematic viscosity, ν, Prandtl Number, Pr, and thermal conductivity, k. Volume expansivity, β, was also calculated as the inverse of the film temperature.

The next step was finding the characteristic length, L_c, of the hot surface. For a vertical plate this is simply the height of the plate (Çengel, Turner and Cimbala 2008, p841).

Next the Rayleigh number, Ra_L, was calculated using Equation 4.8. This Equation includes the acceleration due to gravity, g, for which a value of 9.81 m/s^2 was used.

$$Ra_L = \frac{g\beta(T_s - T_r)L_c^3}{\nu^2}\mathrm{Pr} \qquad \textbf{Equation 4.8}$$

Next the natural convection Nusselt number, Nu, was calculated using Equation 4.9.

$$Nu = \left(0.825 + \frac{0.387 Ra_L^{1/6}}{(1 + (0.492/\mathrm{Pr})^{9/16})^{8.27}}\right)^2 \qquad \textbf{Equation 4.9}$$

Next the convective heat transfer coefficient was calculated using Equation 4.10. This allowed the natural convection heat transfer to be calculated using Equation 4.6.

$$h = \frac{k}{L_c} Nu$$ **Equation 4.10**

4.2.6 Radiation Heat Transfer

The same hot stove surfaces which give energy to the room through natural convection also provide energy by radiation. This amount of energy transferred by radiation, Q_r, was modeled using Equation 4.11.

$$Q_r = A_s \sigma (T_s^4 - T_r^4)$$ **Equation 4.11**

σ is the Stefan-Boltzmann constant and has a value of $5.670X10^{-8}$ W/m^2K^4 (Çengel, Turner and Cimbala 2008, p879.). Equation 4.11 is valid only for temperatures in Kelvin.

The total space heat provided to the room was found using Equation 4.12 which sums the radiation, natural convection, and forced convection heat transfers. Q_{sh} is the final piece of information needed to apply Equation 4.1, which gives the pellet stove efficiency.

$$Q_{sh} = Q_{fc} + Q_{nc} + Q_r$$ **Equation 4.12**

4.2.7 Data Collection

In order to estimate the efficiency of the stove it is necessary to measure several temperatures. All temperatures were measured using K type thermocouples, selected for their ease of installation and appropriate temperature range. Thermocouple outputs were monitored with a digital scanning thermometer which relayed data to a computer for storage. Thermocouples were used to measure the following temperatures:

- Room Air (T_r)
- Heat Tube Air Outlet (T_x)
- Left and Right Stove Sides (T_{sL} and T_{sR})
- Stove Front (T_{sF})

An example plot of temperature data is shown in Figure 4.3: Stove Side Temperature. This plot displays data for the left stove side temperature, measured while burning wood pellets. Notice that the temperature increase over the first twenty minutes of operation as the stove proceeds towards steady state operations. After twenty minutes the temperature curve becomes fairly flat. It was during this steady state that temperature data was collected from a table of values. Temperature data is presented in Table 4.3.

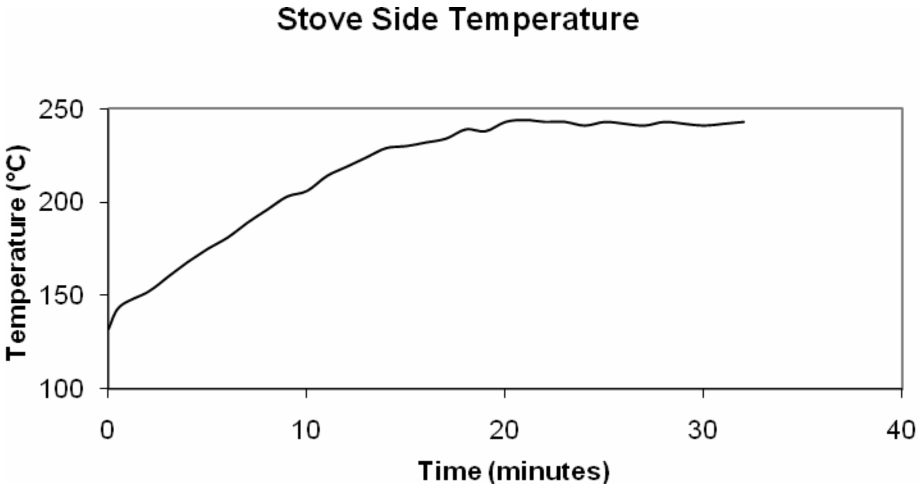


Figure 4.3: Stove Side Temperature

4.3 Results and Discussion

4.3.1 Thermal Efficiency

The data collected for the pellet stove firing premium wood pellets and straw pellets is shown in Table 4.3: Thermal Efficiency Raw Data. Note that only the LHV data was sourced in literature, all other data was the result of measurement by the thesis' author. Dashes indicate that collected data was identical during the test firing of both fuels.

Property	**Wood**	**Straw**
LHV (MJ/kg)	19.0 (Obernberger and Thek 2004)	19.0 (Renström 2006)
m_p (g)	144.1 +/- 0.1	146.5 +/- 0.1
t (s)	240 +/- 1	240 +/- 1
ΔP_x (Pa)	32 +/- 1	34 +/- 1
T_x (°C)	103 +/- 1	98 +/- 1
T_r (°C)	22 +/- 1	22 +/- 1
T_{sL}(°C)	240 +/- 1	220 +/- 1
T_{sR} (°C)	235 +/- 1	224 +/- 1
T_{sF} (°C)	240 +/- 1	215 +/- 1
Boot Diameter (mm)	99 +/- 1	-
Stove Height (mm)	661 +/- 1	-
Stove Side Width (mm)	209 +/- 1	-
Stove Front Width (mm)	414 +/- 1	-

Table 4.3:Thermal Efficiency Raw Data

The measured data in Table 4.3 was used to calculate the many properties outlined in the Methods section using Equations 4.1 to 4.12. The results of these calculations are shown in Table 4.4: Efficiency Results. Again, dashes indicate that data did not depend on fuel selection.

Property	**Wood**	**Straw**
mf (kg/h)	2.161 +/- 0.009	2.197 +/- 0.009
ρ_x (kg/m^3) (Çengel, Turner and Cimbala, 2008)	0.939	0.951
A_x (cm^2)	77 +/- 2	-
V_x (m/s)	8.3 +/- 0.1	8.5 +/- 0.1
m_{ax} (kg/s)	0.060 +/- 0.002	0.062 +/- 0.002
h_x (kJ/kg) (Moran and Shapiro 2000)	376	371
h_r (kJ/kg) (Moran and Shapiro 2000)	295	-
Q_{fc} (W)	4800 +/- 100	4700 +/- 100
T_s (°C)	238 +/- 2	220 +/- 2
T_f (°C)	130 +/- 1	121 +/- 1
ν (m^2/s) (Çengel, Turner and Cimbala 2008)	2.634X10^{-5}	2.522X10^{-5}
Pr (Çengel, Turner and Cimbala 2008)	0.7057	0.7073
k (W/m·K) (Çengel, Turner and Cimbala 2008)	0.03305	0.03235
β (K^{-1})	0.002481 +/- 0.000006	0.002539 +/- 0.000006
Ra_L	1.55X10^9 +/- 0.01X10^9	1.58X10^9 +/- 0.01X10^9
Nu	154.3 +/- 0.4	154.3 +/- 0.4
h (W/m^2·K)	7.66 +/- 0.02	7.55 +/- 0.02
A_s (cm^2)	4120 +/- 10	-
Q_{nc} (W)	683 +/- 7	615 +/- 7

Property	Wood	Straw
Q_r (W)	1600 +/- 20	1380 +/- 20
Q_{sh} (W)	7100 +/- 100	6700 +/- 100
η_p (%)	62 +/- 1	58 +/- 1

Table 4.4: Efficiency Results

The fuel mass feed rate and space heating output are within the stove manufacturer's specifications which are listed in Table 4.2. Please note that uncertainties given are strictly associated with measurement devices and do not account for possible deviations between the selected models (Equations 4.1 through 4.12) and real world behavior. For example, the radiation heat transfer has been modeled as black body radiation, ignoring the effects of geometry and material emissivity.

The final result of the experiment is a thermal efficiency of 62% +/- 1% for wood pellets and 58% +/- 1% for straw pellets. Since this efficiency is measured due to a lack of availability in literature, published values were not available for comparison.

4.3.2 Estimating Stack Losses

Most pellet stoves operate with an excess combustion air ratio of at least 35. This is done to achieve except status from EPA regulations. Because of this large excess air ratio, exhaust stack losses cause relatively large inefficiencies. The stack loss, Q_{sl}, can be modeled using Equation 13.

$$Q_{sl} = m_{as}(h_s - h_r)$$ **Equation 13**

The mass flow rate of stack gas, m_{as}, is measured using a pitot tube and a procedure similar to that used to measure the flow of air through the heat exchanger. Because the pellet stove operates with a large excess air ratio the exhaust gas enthalpy and density are obtained from literature by approximating the gas as air. Equations 4.3 and 4.4 are used to convert the pitot tube differential pressure, ΔP_s, to a mass flow rate of air through the stack. Data used for the stack loss estimate is shown in Table 4.5: Stack Loss Data.

Property	Wood	Straw
T_s (°C)	205 +/- 1	185 +/- 1
h_s (kJ/kg) (Moran and Shapiro 2000)	478	458
ΔP_s (Pa)	23 +/- 1	21 +/- 1
ρ_s (kg/m^3) (Moran and Shapiro 2000)	0.739	0.771
V_s (m/s)	7.9 +/- 0.2	7.5 +/- 0.2
A_{ex} (cm^2)	45 +/- 1	-
m_{as} (kg/s)	0.0264 +/- 0.0009	0.0264 +/- 0.0009
Q_{sl} (W)	4800 +/- 200	4300 +/- 200

Table 4.5: Stack Loss Data

The stack loss is found to be 4300 W for straw and 4800 W for wood, as shown in Table 4.5. This is significant compared to the space heat outputs listed in Table 4.4.

4.4 Recommendations and Conclusions

The method above is used to evaluate thermal efficiency of a residential pellet stove. The method is directly applicable to any residential pellet stove with a design as shown in Figure 4.1. This method of measuring space heat transferred to a room could be extrapolated to other heating devices.

In order to obtain the best results from the fuel ranking tool thermal efficiency should be evaluated for any specific system under consideration. Literature supplies a modest amount of efficiency data, but should only be used if the user has similar equipment and fuels to the author's.

When stack losses and space heat rates are summed they are within roughly 5% of the fuel heating value. This indicates that measurements were, in all likelihood, relatively accurate. Thermal efficiencies for straw and wood fuel were in the 60% range and the stack losses were in the range of 40% of the fuel heating value. This indicates that stack losses are indeed the largest source of inefficiency in this particular biomass space heating system.

Chapter 5

Conclusions

This thesis achieves its objective of developing and demonstrating a biofuel ranking tool. Many methods for selecting biomass fuels previously existed but were based on specific, and often highly focused, sets of factors.

The ranking tool presented in Chapter 3 is a customizable multi-criteria tool. The tool is useful to engineers wishing to help users rank a list of fuels according to how well each satisfies the user's unique performance requirements. The steps in the application of the tool are

- Listing Performance Requirements Through Good Communication with the User
- Defining Performance Indicators in Terms of Measurable Quantities
- Collecting Accurate Data Experimentally or from Literature
- Calculating Performance Indicators Mathematically
- Combining Performance Indicators with Weighting Factors to allow Easy Fuel Ranking

The decision tool is effective only if accurate communication is conducted between the engineer and the user. Communication is critical for generating a list of performance requirements which truly represent the user's needs. Performance indicators corresponding to requirements must be defined by engineers with knowledge of bioenergy systems. Accurate data must be collected, whether taken from literature or measured experimentally. Weighting Factors for performance indicators should be selected through good communication between the engineer and the user.

The tool is demonstrated in Chapter 3. A theoretical example situation involving a pellet stove user with access to three types of pellets is explored. User performance requirements are economic cost, storage space, equipment cleaning, certain air pollutant emissions, and local economic stimulation.

The tool presented in this thesis will rank any list of solid biomass fuels. Within the scope of this thesis ranking is the sole purpose of the tool. The tool is not designed to verify that the fuels are actually acceptable for the user's needs. For example suppose a user had only one requirement, minimized economic cost. The tool can easily be used to rank a list of fuels according to the economic costs associated with each. This ranking can quickly be used to identify the cheapest fuel. Although it is the cheapest option, there is no assurance that this least expensive fuel will actually be within the budget of the user. As demonstrated by this simple example the tool does help users select the fuel with which they will be most happy. It does not verify that they will be *entirely* happy.

It is possible to also use the tool to determine how well a group of fuels perform relative to some standard. This can be achieved by including a fictitious target fuel in the ranking process. It would be easiest to include this fictitious fuel in the ranking process by formulating target values for performance indicators in the fourth step. Target values would be established through communication with the user. In the case of the pellet stove user discussed in section 3.7 a target cost could be developed based on the user's personal finances. The space indicator could be selected by measuring an area of the user's home which he or she is willing to dedicate to fuel storage. The annual ash mass target could be established based on a mass of ash the user feels is reasonable to removed from the stove on a weekly basis, and then multiplying this number by the number of weeks in the user's heating season. Similar logic can be used to develop a target value for any performance indicator.

Once target values for performance indicators have been established they can be assigned to a fictitious target fuel and included in the remainder of the decision process. Including a fictitious target fuel allows the user to make easy comparisons between the single indicators for the actual fuels and the target fuel. Unfortunately, including a target fuel in the ranking process does nothing to change the selection of actual fuels available to the user.

This thesis also presents a method which may be used to evaluate the thermal efficiency of a pellet stove. The thermal efficiency of the stove was measured to be 62% +/- 1% when firing wood pellets and 58% +/- 1% when firing straw pellets. This experiment also demonstrates that changing fuels in a given combustion appliance can lead to changes in thermal efficiency. This experimental method can be adapted to various systems.

Chapter 6

Recommendations

The fuel ranking tool presented in this thesis should be applied to a variety of systems of varying size and combustion equipment design.

The tool presented in this thesis is excellent for ranking biofuels. In the future the tool could be improved by providing a mechanism to allow users to consider new equipment costs, which could be required for the use of fuels not compatible with the user's existing equipment. This would broaden the target audience of the tool by including persons considering the installation of new equipment.

A modification of the combination of performance indicators with weighting factors to include a comparison of each fuels' indicators to target values would improve the tool by allowing it to indicate to the user how well their available fuels perform in comparison to some set standard represented by the target values. Currently the tool ranks fuels but does not indicate how well each fuel performs in reference to some benchmark. Establishing such a benchmark is challenging and was not done in this thesis because the broad range of performance expectations held by biofuel users.

A broader catalog of performance indicators should be developed in future work. This would allow engineers to applying the tool in a more time efficient manner. A catalog of suggested weighting values would also be beneficial for the same reason. A data catalog would also be valuable but this is a much more challenging task – because of the wide variety of equipment, range of fuel qualities, and operating conditions it would be nearly impossible to develop a truly complete catalog of data. Still, current literature is relatively weak in the areas of thermal efficiency and lower heating value so increased publication of these properties would be of value.

Appendix A
Biomass Resource Assessment for Prince Edward Island

A.1 Introduction

Prince Edward Island (PEI) is Canada's smallest province and has a total land area of approximately 5680 km^2. The three largest industries are agriculture, tourism, and fisheries. The climate includes summers with temperatures as high as 30 °C and winters which can include snow covering from November to early April. Land use on Prince Edward Island can be categorized as shown in Table A1: PEI Land Use.

Land Use	Area (km^2)	Percentage of Total
Forest	2570	45
Agriculture	2220	39
Abandoned Farmland	160	3
Wetland	360	6
Transportation	130	2
Other	240	4
Total	5680	100

Table A1: PEI Land Use (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Division 2002)

A variety of biomass materials are available on PEI. This document identifies the most plentiful types of biomass on PEI. Estimates are made of the mass of each material which could potentially be harvested annually. Finally, the annual energy available from each biomass resource is evaluated.

A.2 Agriculture

Agriculture is the largest industry on PEI and is one of the largest sources of biomass in the province. Statistics Canada's Census of Agriculture recorded land areas use for major crops on PEI. This data is presented in Table A2: PEI Crop Areas.

Land Use	Area (Acres)
Hay and Fodder	134,761
Potatoes	108,158
Barley	90,576
Mixed Grain	24,514
Spring Wheat	19,880
Total Crop Production	420,971

Table A2: PEI Crop Areas (Prince Edward Island Department of Environment and Energy 2004)

Hay and fodder are consumed by livestock. The entire above ground portion of hay and fodder crops is normally harvested and fed to livestock. These crops generally produce very little residual biomass which would be available for use as fuel.

Prince Edward Island produces about 1.3 billion kg potatoes annual, accounting for about one third of Canada's potato production. Potato plants produce unmarketed biomass, such as leaves, at a ratio of one mass unit to each four mass units of potatoes (Lal 2005). However, this residual biomass is purposely killed before harvesting to help preserve potatoes. Equipment is not available to gather this excess material which is allowed to compost for soil nutrient recycling (Caseley 2007). For these reasons residual plant matter from potato production is not considered to be a viable fuel.

Occasionally large quantities of potatoes must be disposed of. This can occur for economic reasons or because of poor potato quality (Caseley 2007). The standard methods of potato disposal are burial and composting. Cull potatoes are poorly suited for use as biofuel for several reasons. First, the potatoes are typically over 90% moisture, which means that the heat of vaporization for the potato would actually exceed the heating value (Çengel, Turner and Cimbala 2008). Second, the potatoes are prone to rotting during storage which causes unpleasant odors and attracts unwanted pests. Third, the availability of cull potatoes is difficult to predict and a reliable supply cannot be identified (Caseley 2007).

Prince Edward Island is home to a large potato processing industry. Potato processing operations generate large amounts of potato waste. This material is unsuitable for direct combustion for the same reasons as cull potatoes. Recently, a large potato processor on PEI has installed an anaerobic digestion system which is used to produce gaseous biofuel from potato processing waste (J D Irving Ltd. 2008). This fuel does not fall into the category of fuels which can be ranked by the decision tool presented in Chapter 3 since it is gaseous rather than solid.

Barley, mixed grain, and spring wheat are all examples of cereal crops. These crops are grown for the barley, grain, and wheat they produce. This biomass is sold as food for humans or animals, although grain has sometimes been marketed for use in residential pellet stoves. In general, grains and other cereal crops are not suitable fuels because food market driven prices are too high when compared to other fuels.

Occasionally grain will become contaminated with mold. The common method of disposing of contaminated grain is to mix it with high quality grain in a ratio which is acceptable for livestock feed (Caseley 2007). Barriers to the use of cull grain as biofuel include storage problems. Grain must be stored dry to avoid germination and decomposing (Caseley 2007). Grain storage has also been associated with rodent infestation.

Cereal crops produce residual biomass in the form of straw. Straw is typically baled to make transportation and handling easier. Common round bale specifications include 1.8m diameter, 1.5m length, and 500kg mass (Caseley 2007).

Cereal crops produce straw at a ratio of 1 to 2 mass units of straw per mass unit of cereal (Lal 2005). Straw yields per acre are highly variable and range between 0.5 and 3 tonnes per acre. A yield of 1 tonne per acre is considered an average across all plant varieties and growing conditions (Mol 2007). Factors effecting straw yield include plant species, seed application density, weather, and soil quality. Some common ranges of straw yield are presented in Table A3: Straw Production by Type.

Crop	Straw Yield, tones/acre
Spring Wheat	0.75 – 1
Barley	1 to 1.25
Oats	1.5 to 1.75
Fall Rye	2 – 3

Table A3: Straw Production by Type (Mol 2007)

Straw grown on PEI is often used as animal bedding. Used bedding is spread on fields as a combination fertilizer and final disposal method. Straw which is not used as animal bedding is often chopped and left in fields for composting. This is done to improve soil quality and to provide a method of disposal for straw. Many fields are rotated through cycles of cereal and potato production. Some potato producers dislike straw compost because of the slow decomposing process (Caseley 2007). Composting straw can be a host for mold and scab organisms in potato fields. Decomposing straw also decreases valuable soil nitrogen which is another disincentive to straw compost for potato growers (Caseley 2007).

Based on average estimates of straw yields from Table A3 and crop areas from Table A2 there are approximately 143807 tonnes of straw produced on PEI annually. Assuming a lower heating value of 14.9 MJ/kg (Kær 2005) this material has the potential to provide $2.14 \mathrm{X} 10^9$ MJ. Estimates are unavailable for the quantities of straw which are used for animal bedding and soil enhancement, so knowing how much could be used as biofuel is difficult.

One Prince Edward Island business makes pellet fuel from local straw. This fuel is intended for combustion in burners designed for straw pellet fuel (Mackay 2007). Straw typically has the fuel properties listed in Table A4: Straw Fuel Properties.

Property	Value
Bulk Density	40 kg/m^3 (Loose) (Mani, Tabil and Sokhansanj 2006) 125 kg/m^3 (Baled) (Caseley 2007)
Ash Content	8.3% (Mani, Tabil and Sokhansanj 2006)
Moisture Content	8.3% (After Indoor Winter Storage) (Mani, Tabil and Sokhansanj 2006)
Lower Heating Value	14.9 MJ/kg (Kær 2005)

Table A4: Straw Fuel Properties

After being used as bedding material the straw fuel properties change, with ash content increasing to the 20% range and higher heating value dropping to 11.5 MJ/kg. These changes are mostly due to dirt mixed with the straw during handling and the addition of animal waste (Koyuncu and Pinar 2007). Used straw bedding has been used as fuel for biomass stoves in developing countries, but this does not commonly occur in industrialized countries.

A.3 Forestry

Forests account for the majority of land use on PEI. 263 000 hectares, 45% of the province's total land area, are wooded. PEI forests are comprised of nearly equal volumes of hardwood and softwood (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002). Hardwoods found on PEI include red maple, sugar maple, yellow birch, poplar, white birch, and beech. Softwoods include red, black, and white spruce, white pine, and balsam fir. Hardwood growth rates exceed harvest rates on Prince Edward Island (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002). The majority of hardwood harvesting occurs in mixed stands where valuable softwood is harvested for the timber industry. Because of this trend softwood covered areas in the province are decreasing while hardwood covered areas are increasing (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002).

The forest industry on PEI provides raw material for a variety of products. The major product is sawlogs used for lumber production. Pulpwood and fuel chips are the next largest markets. Remaining markets are firewood and manufactured wood products such as veneer and oriented strand board (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002).

Tree harvesting may be performed in one of two ways. Whole tree harvest involves removing most of the above ground biomass from a forest while stem only harvesting leaves tree tops and branches on the forest floor. Studies performed on PEI suggest whole tree harvest results in lower soil nutrient levels and slower re-growth of newly planted trees than stem only harvesting (Mahendrappa et al. 2006). For this reason caution should be used when deciding how aggressively to recover residual biomass from logging operations.

PEI forests currently provide biofuel which makes up roughly 6.5% of the province’s total energy use and nearly all of the provinces renewable energy use (Prince Edward Island Department of Environment and Energy 2004). Most of this fuel is in the form of cordwood, with 35% of Islanders using wood as their primary or secondary home heating fuel. A percentage of wood used for energy in the province is in the form of wood chips. One large district heating system on PEI uses approximately 40 000 tonnes of wood chips. Wood chips are also used in heating systems for a few other buildings within the province (O'Connor 2007). In the past sawmill residue was used as fuel but in recent years far less milling is occurring on PEI, with most wood being shipped off island to be milled (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002).

Fuel chip production per area of forest is highly variable. In some areas the amount of material remaining after selling high quality wood to higher paying markets is too small to justify the transport cost of chipping equipment. In other areas, particularly where mature trees grow close together and quality is low, yield of chips are as high as 100 tonnes per acre (O'Connor 2007). Most areas have chip yields between these limits due to mixtures of high and low quality trees. Some fuel properties of logging residue chips are listed in Table A5: Wood Chip Fuel Properties.

Property	Value
Bulk Density	215 kg/m^3 (40% Moisture) (Strehler 2000)
Ash Content	2% (Wikström 2007)
Moisture Content	60% (Fresh) 40% (Naturally Dried) (Wikström 2007)
HHV	10.1 MJ/kg (40% Moisture) (Strehler 2000)

Table A5: Wood Chip Fuel Properties

Some assumptions must be made to estimate the mass of fuel wood which can be harvested annually on PEI. These include:

- Average Yield per Area
- Time to Grow To Maturity
- Total Available Forest Area

The simplest model assumes that the entire area of forest is available for production. Harvested areas are replanted and left undisturbed until they reach maturity, at which time they are used for chip production. A reasonable estimate for average chip yield on PEI is 20 tonnes per acre and a reasonable time period for regrowth is 35 years (O'Connor 2007). This data, along with the total forest area of 642 200 acres, allows the calculation of an annual chip supply of 367 000 tonnes. This estimate is likely a high one, as some woodlot owners are unwilling to sell their wood. This estimate does consider the market for other forest products, since 20 tonnes per acre is an estimated chip yield based on some acres being harvested for saw logs or pulpwood and contributing only tree tops and branches to chip production.

Based on the estimate of 367 000 tonnes of wood chips and a higher heating value of 10.1 MJ/kg for fresh forest residue at 40% moisture content (Strehler 2000) this resource has an energy content of $3.7X10^9$ MJ. 40% is the lowest moisture content which can be expected for fresh forest residue using natural drying techniques (Wihersaari 2005a).

Throughout the 1990’s total forest area on PEI declined by roughly 6% (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002). This decline was partly due to aggressive harvesting of softwood. Softwood harvesting was motivated by market demand. Production rates were able to increase during this time because mechanized timber felling became widely used. Also during this time sawmill technology improved and allowed the use of sawlogs which were formerly considered undersized. Much forest cleared in the 1990's was converted to agricultural land (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002). Declining forest area should be considered when estimating possible fuel production in the long term future.

The fuel chip market is valuable to the forestry industry because it offers a market for wood which is below the quality standards of other forest products. Chip production can also play a role in woodlot management. Poor quality trees can be thinned from stands and sold as chips, allowing more space for higher quality trees to grow (Prince Edward Island Department of Agriculture and Forestry, Forestry and Land Resource Modeling Devision 2002). The biofuel industry could provide a market for more hardwood trees on PEI, which are currently harvested at rates below their growth rate, as mentioned above.

A.4 Municipal Solid Waste

A municipal solid waste disposal program has been developed, implemented, and operated by a provincial crown corporation in PEI. This program, called Waste Watch, is successful at diverting over 60% of solid waste from landfill (Island Waste Management Corporation 2005). Household and commercial waste is separated into three categories before collection. The categories are recyclable materials (including metal, plastic, and paper), compost (organic material other than recyclable paper), and waste (non-recyclable and inorganic materials). Masses of collected Waste Watch materials and disposal methods for 2005 are listed in Table A6: 2005 Refuse Data.

Material	Mass (tonnes)	Disposal Method
Waste	22 500	Landfill
Waste	26 000	Incineration (District Heating Plant)
Compost	26 000	Aerobic Digestion (16 000 tonnes Finished Product)
Recyclable (Paper, Plastic, and Metal)	15 000	Recycling Out of Province
Used Tires	2000	Recycling Out of Province

Table A6: 2005 Refuse Data (Island Waste Management Corporation 2005)

The waste materials above do not include construction and demolition waste, which is discussed in a later section.

Compost materials are aerobically digested (Island Waste Management Corporation 2005). Finished compost is offered to the public free of charge at certain times of year and available for purchase at others. Some hobby gardeners use this material for soil enhancement.

Waste from the province is disposed of by two methods. Some waste is disposed of in a landfill and other waste is incinerated. Energy from incinerated waste is a major input to the province's largest district heating system. Household waste provides roughly 37% of the energy input to a 40 MW district heating system. Incinerator exhaust is treated using powered activated carbon injection to ensure emissions are within guidelines of the Canadian Council of Ministers of the Environment (CCME) (Island Waste Management Corporation 2005). Incinerator emissions were evaluated in 2005 by an engineering consulting firm to verify compliance with CCME guidelines (Island Waste Management Corporation 2005).

Municipal solid waste is a potential fuel which is available in many regions. Garbage is a mixture of many distinct fuels. The heating value of garbage is improved by removing noncombustible materials such as metal and glass. Refuse fuel properties vary with geographic region and also with time of year (Tillman 1991). Higher heating values for some common mixed waste components are listed in Table A7: Garbage Heating Values. These materials represent components of common unsorted refuse, some of which are composted or recycled on PEI. The heating value of Waste on PEI is likely higher than the value listed for mixed waste due to the higher content of non-recycled plastics and the lower content of metal.

Material	**HHV (MJ/kg)**
Newsprint	14.5
Magazine Stock	12.7
Textiles	15.3
Plastics	27.0

Material	HHV (MJ/kg)
Yard Waste	9.3
Food Waste	7.6
Mixed Waste	14.0

Table A7: Garbage Heating Values (Tillman 1991)

Based on the average heating value of mixed waste and the annual mass of landfill waste on PEI, this landfill material has an energy content of approximately $3.2X10^8$ MJ.

A.5 Construction and Demolition Waste

Construction and Demolition Waste (CDW) is accepted for final disposal via landfill on PEI at privately owned and operated sites, regulated by the province's Environmental Protection Act – Waste Resource Management Regulations (Prince Edward Island Environmental Advisory Council 2005). Under these regulations CDW is defined as non-hazardous material which is normally used to build roadways, buildings, other structures and walls, and landscaping materials. These materials include soil, asphalt, wood, brick, mortar, drywall, reinforced concrete, and plaster. CDW specifically excludes chemically treated wood, which by regulation is disposed of in the same landfill as waste from municipal garbage collection (Prince Edward Island Environmental Advisory Council 2005).

Wood from CDW can be treated as a source of biofuel. When used to replace fossil fuels this fuel offsets even more greenhouse gases than other types of wood fuel (Petersen and Kristin 2006). On PEI, it is not feasible to use wood from CDW as fuel on a large scale since CDW is deposited at disposal sites in mixed loads which include other noncombustible materials. In order for CDW wood to be a viable fuel it would need to be separated from other CDW materials. A recent report to the provincial Minister of the Environment, Energy, and Forestry by the Environmental Advisory Council has suggested that this sorting should be required by regulations and that recovered wood should be used as fuel for the 40 MW district heating system located in the province's capital city of Charlottetown (Prince Edward Island Environmental Advisory Council 2005).

At this time data is not available to show the mass of wood available from construction and demolition on PEI. This data is unavailable because mixed materials are disposed of in several privately owned landfill sites (Myers 2006).

A.6 Conclusions

Prince Edward Island is a province with biomass resources available from agriculture, forestry, and waste management. Specific materials, quantities, and energy values are listed in Table A8: PEI Biomass Resources. The heating value for compost is an average of the heating values for food waste and yard waste from Table A7: Garbage Heating Values. Although municipal waste has a very low content of organic material it is included in the table because of its similarity in mass and energy content to compost.

Material	Mass (tonnes/year)	Higher Heating Value (MJ/kg)	Energy (MJ/year)	Competing Markets
Straw	143 807	14.9	$2.1X10^9$	Animal Bedding Soil Enhancement
Forrest Biomass	367 000	10.1	$3.7X10^9$	Soil Enhancement Lumber Pulp Manufactured Wood Nature Areas
Municipal Waste	22 500	14.0	$3.2X10^8$	Landfill
Municipal Compost (Pre-Processing)	26 000	8.5	$2.2X10^8$	Soil Enhancement

Table A8: PEI Biomass Resources

As shown in Table A8: PEI Biomass Resources Straw and Forrest Biomass can provide energy which is an order of magnitude larger than either waste, compost, or even these two materials together. The energies listed in Table A8 could be used to determine wether the materials in the table could provide a large enough source of fuel for a specific user. This information would be used to determine which materials could be included in a list of fuels to which the fuel ranking tool of Chapter 3 would be applied.

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