EVALUATION OF WOOD BIOMASS UTILIZATION FOR THE GREENHOUSE INDUSTRY IN BRITISH COLUMBIA

By

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B.Sc., The University of British Columbia, 2006

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

July 2008

Abstract

The Canadian greenhouse industry is challenged by high operating costs as the natural gas price has been increasing and fluctuating over the past few years. Natural gas is the primary energy used by the greenhouse industry to generate heat and carbon dioxide (CO_2) to enhance the crop productivity. There are concerns about the global warming effect caused by natural gas usage as it is a non-renewable energy. Therefore, the greenhouse industry is seeking an alternative energy source which is economical, renewable, and environmentally friendly to reduce the fossil fuel consumption. Wood biomass, mainly wood pellets and wood residue, is a renewable energy used in the greenhouses to decrease the natural gas demand. However, the long-term economic value, the air quality emission, and the long-term resource availability are the main barriers for the industry to convert into wood biomass boiler. The main objectives of this study are to 1) evaluate the economic feasibility of using wood biomass for the greenhouse heating application, and to analyze the associated impacts of the technical and economical changes, and 2) determine the optimal biomass mix with the consideration of emission limits and resources availability constraints. Specific case studies will be considered in this research to achieve the mentioned objectives.

The results of the techno-economic analysis showed positive net present value (NPV) for the four cases considered: using wood pellets or wood residue boiler, with or without an electrostatic precipitator (ESP), to generate portion of heat demand for a greenhouse. Although the decision making would be affected by the price changes and the size of a greenhouse, a positive NPV was determined from a pure economic view point. Wood biomass is a "carbon neutral" material; therefore, combusting wood biomass could reduce over 3,000 tonnes of CO_2 equivalent greenhouse gases annually. Sensitivity analyses indicated that wood biomass attractiveness would increase with higher natural gas prices or larger energy contributions from wood biomass. The optimization study suggests a feasible biofuels mix for the case study of a 2 ha flower greenhouse and a 7.5 ha vegetable greenhouse. The model was solved considering the inclusion of an ESP system to ensure the air quality limits were satisfied. The optimal result was compared to an existing 2 ha flower greenhouse and revealed almost 20% reduction on the total fuel cost per year.

Table of Contents

List of Tables

List of Figures

Glossary

Boiler efficiency	The ratio of energy output to energy input.
Linear Programming model	A mathematical model that maximizes or minimizes one or more objectives considering several constraints. The objective function and constraints are in the form of linear equations.
Net Present Value (NPV)	The sum of initial investment and the present worth of a project's future cash flows over the lifespan of the project.
Optimization model	A mathematical model that uses mathematical techniques to identify an optimal solution consistent with criteria supplied.
Particulate matter (PM)	A mixture of extremely small particles and liquid droplets suspended in the air. The particle sizes range from 0.5 to 10.0 μm in diameter deposit in human's respiratory system causing irritation and other respiratory disease to humans.
Sensitivity analysis	Analysis of the effect of changes in the parameters of a model on the final result.
Techno-Economic study	A study of combining the technical and economical parameters which could affect the economics of a project.
Wood biomass	A renewable energy which includes wood chips, sawdust, wood pellets, hog fuel, forest and sawmills residues, and chemical-free wood waste.

Acknowledgement

I would like to acknowledge my supervisors, Dr. Taraneh Sowlati and Dr. Shahab Sokhansanj, for the time they dedicated to me and to my work and for their support. I sincerely thank them for providing me this opportunity to complete a Master's degree. This research would have been impossible without their expertise, helpful comments, and encouragements.

I would also like to thank Dr. Tony Bi and Mr. Staffan Melin (my supervisory committee members) and Dr. Fernando Preto for their support and comments towards my work. I appreciate the valuable insight that they provided to me and to my research.

I truly appreciate the time and support of Dr. Anthony Lau, the external examiner of my thesis, and Dr. Philip Evans, the chair of my examining committee.

I would also like to thank all members of the Faculty of Forestry, the Wood Science Department, the Biomass and Bioenergy Research Group, and the Industrial Engineering Research Group, who helped and supported me during my graduate study.

This research is funded by the Natural Sciences and Engineering Research Council of Canada through a Strategic Project and by the Natural Resources Canada. The contribution of the Wood Pellet Association of Canada for providing data on wood pellet production and consumption is appreciated.

Lastly, I would like to thank my family and friends for their continuous support. My special thanks go to Mr. Kenneth Chau, Ms. Gigi Chau, Miss Jenny Chau, and Mr. Graeme Dick for helping me through my academic life, and to my dear parents without whom I would not be able to succeed.

Co-Authorship Statement

The research studies carried out in this thesis were defined and designed by Dr. Taraneh Sowlati and Dr. Shahab Sokhansanj. The case study was suggested by Dr. Sowlati. The research activities, including reviewing the related literature, interviewing industry experts, gathering data on the case studies, evaluating the technical and financial data, developing and running the Linear Programming model, performing the sensitivity analyses, and analyzing the results, were conducted by Jo Chau. The thesis was prepared in manuscript style. A version of Chapter 2 has been accepted for publication in Applied Energy, a version of Chapter 3 and 4 has been submitted for publication. The manuscript preparation was performed by Jo Chau. Also, Dr. Sowlati, Dr. Sokhansanj, Mr. Staffan Melin, Dr. Fernando Preto, and Dr. Tony Bi co-authored in the manuscript chapters.

Chapter 1. Introduction

1.1 Greenhouse industry background

The Canadian greenhouse technologies have been developed rapidly with the supports of research institutions to overcome the climatic limitation for vegetables production (AAFC 2008). Heat, water, nutrients, pests and diseases are controlled in a greenhouse such that plants are grown under prefect condition. As a result, the production per area in greenhouses is approximately 15 to 20 times more than that of the equivalent field area (BCMAFF 2004). The greenhouse industry in Canada had a total area of 2,134 hectares (ha) and generated C$2.3 billion revenue in 2006 which is 180% more than the revenue generated by this industry in 1995 (Statistic Canada 2006, Statistic Canada 2007).

The total greenhouse sales are mainly contributed by the provinces of Ontario, British Columbia, and Quebec (Figure 1.1). Ontario accounts for more than 50% of the greenhouse area and total greenhouse sales in Canada, followed by British Columbia (BC) with 511 ha of greenhouse area and C$570 million of total sales. The greenhouse industry in BC is typically separated into two main categories: flowers and vegetables. Flower greenhouse products include fresh-cut flowers, potted plants, and bedding plants. Since flowers and bedding-plants generate higher profit than vegetables, approximately 55% of the total greenhouse sales in BC were associated with the flower greenhouses (Statistic Canada 2007). Vegetable greenhouse growers in BC mainly produce four types of vegetables: tomatoes, cucumbers, lettuce, and peppers. Approximately 75% of the BC greenhouse vegetables are exported to US, with the remaining exported to Asia and Canadian domestic markets.

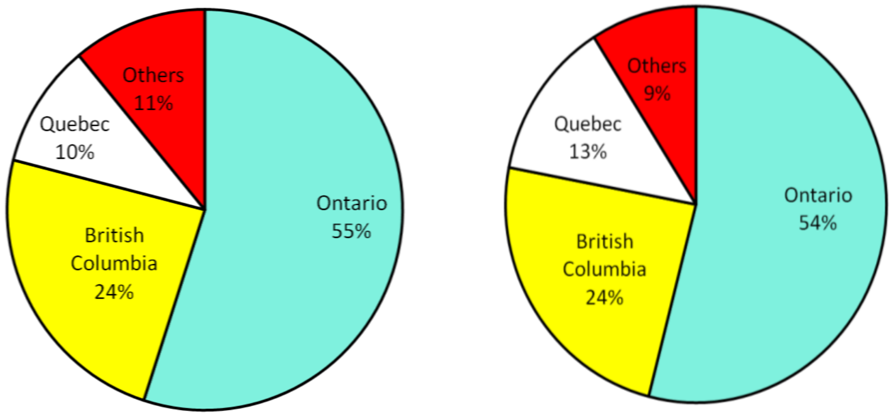

Figure 1.1. Total greenhouse sales (left) and total greenhouse area (right) in 2006. Data from (Statistic Canada 2007)

1.2 Problems

To enhance crops production, indoor temperature and carbon dioxide (CO_2) levels are monitored and controlled by computers. On average, the indoor temperature is kept at 16°C to 27°C depending on the greenhouse location, building structure, and crop types. The CO_2 concentration in a vegetable greenhouse is about 700 – 800 parts per million volume (ppmv) with a maximum threshold level up to 1,500ppmv depending on the type of crop (Nelson 1998). Natural gas is the primary energy source to produce heat and CO_2 for greenhouses. Natural gas combustion is a more efficient and cleaner process than that of other fossil fuels. The flue gas from the combustion is considered to be clean enough by the industry for direct CO_2 injection. However, natural gas is a non-renewable energy which produces fossilized carbon and greenhouse gases. The CO_2 and other greenhouse gases emitted from fossil fuels are one of the main causes of global warming effect. Therefore, the environmental impacts have become one of the concerns related to the substantial use of natural gas.

The average natural gas price has increased significantly from C$2.00/GJ in 1995; and in the past few years, the natural gas price was fluctuating between C$5.00/GJ and C$10.00/GJ (Melin 2007). In 2005, the Canadian greenhouse growers spent C$1.45 billion on fuel which accounts for 74% of the operating expenses (labour and fuel costs) (Statistic Canada 2006). With the fluctuating and increasing natural gas price, the future operating costs are unstable and unpredictable for the greenhouse industry. In addition, the growth of total greenhouse sales has slightly declined due to the increased competition from import markets; it created an economic challenge to the industry. Consequently, the greenhouse industry in BC is seeking an alternative way to dissolve the financial and environmental concerns of using natural gas.

Wood biomass utilization for heat generation is one of the alternatives to reduce the natural gas demand. Wood biomass is considered as a sustainable energy source since it could be reproduced on a continuous base from the natural environment (Boyle 2004). Wood biomass includes wood chips, sawdust, wood pellets, hog fuel, forest and sawmills residues, and chemical-free wood waste. BC is the largest lumber-producing province in Canada which accounted for 50% of the lumber production in 2004 (Bradley 2006). Wood biomass is mainly a by-product from the lumber production. Approximately 1.85 million dry tonne (t) of wood residues were produced for pulp and paper production, in-plant heat generation, pellets or briquettes production, and energy generation in 2004. Although wood biomass is a low cost material which is economical to use, the inconsistency in material quality could increase the transportation and material handling costs. The bulk density of sawdust ranges from 91.3 – 155.4 kg/m^3 and 182.6 – 270.7 kg/m^3 for loose packing and dense packing, respectively (Walawender et al 1997). The heat value of wood residue ranges from 10 – 20 GJ/t depending on the materials moisture content. By densification, a more consistent material such as wood pellets (bulk density of 650 kg/m^3 and heat value of 17 – 18 GJ/t) can be produced to ensure the material quality. Although additional costs would be added for wood biomass pelletization, the natural gas price would still be higher than that of wood pellets. The average wood pellets price is C$5.00/GJ – C$7.00/GJ.

Wood biomass is considered to be a carbon-neutral material as the amount of carbon released during complete combustion is equal to the amount of carbon absorbed during the photosynthesis process. Although the flue gas of wood biomass combustion cannot be used for CO_2 injection to greenhouses, the CO_2 emission does not affect the overall carbon inventory. Wood biomass has high ash content and emits more particulate matter (PM) which could affect the local air quality during combustion. Metro Vancouver is proposing a new amendment to the Air Quality Management bylaw, which introduces emission limits to all boilers and heaters that are fuelled by natural gas, wood biomass, and oil (Metro Vancouver 2008). The new bylaw, when approved, will obligate a wood biomass boiler user to use an advanced emission control system to satisfy the emission limits.

Although there are an increasing number of greenhouses installing wood biomass boilers in the Lower Fraser Valley of BC (Melin 2006), the greenhouse industry still has some concerns regarding the conversion into wood biomass heating systems mainly due to the long-term biomass availability and the financial uncertainty. The Canadian wood pellets production reached 1.4 million t in 2006 and there is an increasing trend of wood pellets production due to the mountain pine beetle (MPB) infestation (Peksa-Blanchard 2007), however, approximately 70% of the total production was exported to European markets. The remaining is distributed in the domestic and US markets for animal bedding and power generation. With the increasing demand for wood pellets and wood residue, the wood biomass price is expected to increase in the near future. In addition, the capital cost of a wood biomass boiler is more expensive than a natural gas boiler. A wood biomass system has a more complex design and requires a storage system for material inventory. Depending on the boiler size, a wood biomass boiler capital cost, including the cost of boiler equipment, storage system, and emission control system, ranges from C$125 – C$166/kW (Geletukha el at 2000), whereas the capital cost of a natural gas boiler is in the range of C$10 – C$30/kW (Oskarsson 1997). With the aforementioned concerns, the greenhouse industry should evaluate a wood biomass project considering all technical, economic, and environmental factors in the decision making process.

1.3 Literature review

Wood fuels were one of the most important traditional energy sources in the ancient time. However, they were rapidly replaced since the discovery and development of fossil fuels, especially during the Industrial Revolution in the early 1900s (Boyle 2004, Goodstein 2004). Approximately 80% of the primary energy is produced from fossil fuels which are the most important energy sources nowadays (EIA 2007). Fossil fuels are defined as non-renewable energy which will emit fossilized carbon and greenhouse gases, causing the global warming effect. Due to the environmental concerns and the energy crisis, a number of studies on renewable energy technology development, economic analysis, and supply chain management have been done to evaluate the opportunity of reducing fossil fuels demand. The economic studies were completed in different countries, mainly in Europe where renewable energies were promoted; and the studies were focused on technologies such as combustion, gasification, and combined heat and power generation (CHP) (Kumabe et al 2008, Tripathi et al 1998, Nouni et al 2007, De Lange and Barbucci 1998, and Anselmo Filho and Badr 2004).

Bridgwater (1995) discussed the technical and economic feasibility of biomass gasification for power generation. Since gasification was still developing during the study period, the capital cost of such system was expensive. The estimated capital cost for a 10MWe integrated gasification plant was approximately US$35 million. The results showed that increasing system capacity (power output) could reduce the total capital cost. In addition, processing low-cost materials such as waste and residue or relying on fiscal incentive such as carbon tax could increase the potential of using wood biomass. However, Bridgwater (1995) did not quantify the potential savings or benefits of biomass gasification by any economic evaluation method.

To present a more precise economic estimation of the investment on biomass energy generation system, Keppo and Savola (2007) completed an economical evaluation of small biofuels fired CHP plants by formulating an energy system model (MODEST), a mixed integer linear programming model. The objective of the optimization model was to minimize the discount production cost considering the technical and operational characteristics of three power plants and the weather condition in Finland. The production cost was estimated to be €14.84/MWh – €15.43/MWh for the three studied power plants, which was approximately 3% more than that of the existing oil system. However, it was believed that the increased cost could be paid off with the increase in electricity price.

Similar to Keppo and Savola's study (2007), Sundberg and Henning (2002) used MODEST to optimize the investments and operation of a CHP plant in Sweden. The study compared the energy production cost of natural gas system and wood chips CHP system. The model also considered incentives such as governmental grant and fuel tax to increase the competitiveness of biomass system. The total energy cost for wood chips (SEK125/MWh), without governmental grant, was approximately 25% less than that of the natural gas. High capital investment is the major reason to the reduced use of biomass; therefore, high energy price, heavily taxed on fossil fuels, or governmental subsidization could make a biomass system profitable.

Instead of focusing on the energy production cost, Schneider and Kaltschmitt (2000), Dornburg and Faaij (2001), and Caputo et al. (2005) expanded their economic studies to include the material handling logistics costs. Unlike natural gas, biomass requires a more complex logistic system which could increase the energy production cost. Their studies considered the transportation factor to determine the feasibility of biomass energy utilization. Since biomass is mainly by-product or residue from various productions, the low material cost off sets the additional processing and transportation costs.

In order to increase the competitiveness of biomass, optimization model can be used to determine the optimal strategic plan for utilizing or producing biomass with the minimal cost. An optimization model is a mathematical model which determines a feasible solution to satisfy a single objective (linear programming) or multiple objectives (multi-objectives programming) under a set of constraints or limitations. While a multi-objective model is usually used to solve a problem with two or more contradicting objectives, linear programming (LP) model is a more common and simpler method to determine an optimal solution for a decision making problem. Applications of optimization models include transportation scheduling, production planning, financial decision making problem, and decision support for district development in different countries (Hahn 1984, Herrero et al 2007, Chinese and Meneghetti 2005).

Cundiff et al (1997) developed a mathematical model to determine an appropriate monthly shipping schedule from various switchgrass farms to storage facilities and to the central energy plant, and to determine a schedule of storage capacity expansion to accommodate biomass due to weather condition. The goal of this model was to minimize the transportation and construction costs and the penalty cost due to loss of biomass quality and failure of satisfying the central plant demand. The model was subjected to the limitation of farm supply, power plant demand, existing storage capacity, and the quality loss due to storage period and weather condition. Based on the suggested scheduling from the model, the total cost was minimized to \$13-\$15/dry Mg. Cundiff et al's model determined the scheduling from a purely economic point of view. Instead of minimizing the total cost the LP model can also maximize the energy production.

Sartori et al (2001) developed an LP model to determine the optimal sugarcane plantation plan in order to maximize the energy production. The soil condition in different areas with varieties of sugarcane could affect the energy production. In their model, the area limitation, the average production for each variety, and the amount of crop residue were considered. The model returned a variety of sugarcane in each area by which the total generated energy was maximized. Sartori and Florentino (2007) then developed another LP model to maximize the energy balance by considering the difference of generating and consuming energy in the process of transferring sugarcane from the plantation field to the processing centre. This model did not only consider the limitations in the planting area and sugarcane diversity, but also considered the restriction from the local mill demand. The results from the model provided a realistic and efficient plantation plan to optimize the biomass energy production; and it was believed that the increase of biomass production could reduce the environmental problems (Sartori and Florentino 2007).

Although biomass is a renewable energy, there are emissions generated to the atmosphere during the energy production. Containment of emissions could be included in the optimization model to reduce or limit the emission from combusting or using biomass. Linares and Romero (2000) developed a multi-objective model which minimized the total cost of installing and operating a power plant, and the emission of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxide (NO_x). The multi-objective model could evaluate both financial and environmental aspects to determine the best balance between the two issues. However, a method was used to establish a weighting factor to the objective functions. Depending on the importance of each objective function, a pay-off matrix for different scenarios was calculated. The matrix showed that by increasing the weighting factor of CO_2, SO_2, or NO_x emission, the total cost became more expensive. Therefore, the decision could be affected by the weighting factor of each objective function. The weighting factor could include individual bias, but could also provide valuable information from the society's point of view (Linares and Romero 2000).

Instead of including the environmental aspects as an objective function to form a multi-objective model, an LP model can also include the environmental constraints if there is an established level of emission allowed by the government. Nienow et al (2000) constructed an LP model to determine the mix of biomass fuel and coal in order to minimize the total cost for a power plant in Michigan City, Indiana. The model considered the energy provided, environmental regulations, and other technical constraints. One of the environmental regulations was on the sulfur dioxide (SO_2) emission which has to be less than 575 g SO_2/GJ of fuel burned. The model returned an optimal fuel mix which was feasible for the described situation in the study, and which satisfied all regulations that applied to the facility.

Among the reviewed studies, a few focused on the investment and operating cost of a biomass boiler. Most of the studies investigated the economic aspects of the biomass supply chain management, from biomass plantation to district heating development. However, few studies have examined the opportunities of combusting wood biomass for heat generation in the greenhouse industry. By performing an economic evaluation and an optimization study, this manuscript will indicate the opportunity of wood biomass utilization for the greenhouse heating application.

1.4 Research objectives

The objectives of this research are as follows:

1. To evaluate the economic feasibility of using wood biomass for the greenhouse heating application.

   To achieve this objective, the economic feasibility of wood biomass combustion in a greenhouse located in the Lower Mainland of BC will be analyzed. A techno-economic analysis will assess the cost benefits of using wood biomass to generate part of the heat for an average-sized greenhouse. The Net Present Value (NPV) method will be applied to determine the financial indicator of four different scenarios: a wood pellets boiler or a wood residue boiler to generate 40% of the total heat demand, each with or without an electrostatic precipitator (ESP) for Particulate Matter (PM) control.

2. To analyze the impact of changes in technical and financial factors on the NPV of using wood biomass for heat generation.

This objective will be achieved by performing sensitivity analysis on the NPV of the scenarios considered in the techno-economic assessment. This will be done by changing the economic and technical parameters in the NPV model, such as fuels price and greenhouse size, and evaluate the changes in the results.

3. To determine the optimal biomass mix (pellets and residue) with the consideration of emission limits and the constraints of resources availability and technologies requirement.

   This objective will be accomplished by determining the optimal fuel mix for a studied greenhouse to generate the required heat demand with the minimum annual total cost. A Linear Programming (LP) model will be developed to determine the optimal fuel mix with technical and environmental constraints applied to the model. Two case studies will be considered: a two hectares flower greenhouse and a 7.5 hectares vegetable greenhouse.

1.5 Dissertation outline

The organization of this thesis is as follows: Chapter 2 focuses on the first objective, the economic feasibility of wood biomass for heat generation in a greenhouse, using the NPV method. The industry barriers and the analysis are explained and the results and discussion are presented. Chapter 3 is an extension study of the techno-economic analysis to fulfill the second objective. The importance of conducting sensitivity analysis and the changes of the fuel price, the wood biomass energy share, and the system capacity are included. Chapter 4 presents the development of the LP model to satisfy the last objective. A detailed explanation of each constraint, including heat demand, technology, resource availability, materials moisture content, and emission limitations, is provided. This chapter also includes the sensitivity analysis of the feasible solution and the discussion of the results. Chapter 5 is the conclusion chapter for the research. It indicates the limitations of this study as well as the suggestions of further studies regarding to the wood biomass usage for the greenhouse industry.

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Chapter 2. Techno-Economic Analysis of Wood Biomass Boilers for the Greenhouse Industry

2.1 Introduction

The greenhouse vegetable industry is an important sector of the Canadian agri-food industry with total sales of about $750 M in 2001 (Agriculture and Agri-Food Canada 2004). The main greenhouse crops produced in Canada are tomatoes, peppers, cucumbers and lettuce, which are mostly exported to the US. British Columbia (BC) accounts for 27% of the total greenhouse vegetable sales (Agriculture and Agri-Food Canada 2004) and provides 2600 FTE (Full Time Equivalent) employment in 2002 (BCMAFF 2003).

Vegetable greenhouses require heat and carbon dioxide (CO_2) to enhance crop productivity (Nelson 1998). Heat is used to adjust the indoor temperature and humidity, while light, water, and carbon dioxide is required for photosynthesis. Most greenhouses in BC operate with two or more boilers; one or more function as the primary heat source, while others as backup systems. A back up is required by insurance companies to prevent crop damage caused by the breakdown of the primary heat source. Natural gas boilers are traditionally preferred because of their low capital cost, high combustion efficiency (Timmenga & Associates Inc 2005) and most importantly, the carbon dioxide supply from the boiler flue gas.

The fuel cost, for providing heat and CO_2, represents about 28% of the operating cost of a greenhouse in BC (BCMAFF 2003). The recent rising and fluctuating natural gas prices have forced greenhouses to consider alternative fuels, and wood biomass is one of the options. In general, the prices of wood residue and wood pellets are lower and more stable than that of natural gas. The number of wood burning boilers installed in greenhouses in the Greater Vancouver Regional District (GVRD) and the Fraser Valley Regional District (FVRD) has been increasing since 2001 (Figure 2.1). In 2006, Delta Research Corporation (Melin 2006) conducted a survey to investigate the status of wood residue and wood pellets heating systems in the greenhouse industry within the GVRD and FVRD. The survey indicated that the price of wood pellets had been stable for the past five years around C$5.00/GJ and was predicted to be

* A version of this chapter has been accepted for publication. Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S. and Bi, X (2008) Techno-economic analysis of wood biomass boilers for the greenhouse industry. Applied Energy

steady for a number of years. For the same period, the price of natural gas, delivered under contract, ranged between C$5.00/GJ to more than C$14.00/GJ with an average of C$8.00/GJ (Figure 2.2). Melin (2006) concluded that switching to biomass as an energy source could generate savings on fuel cost. The survey also predicted that more than 12 wood burning boilers will be installed within the next few years.

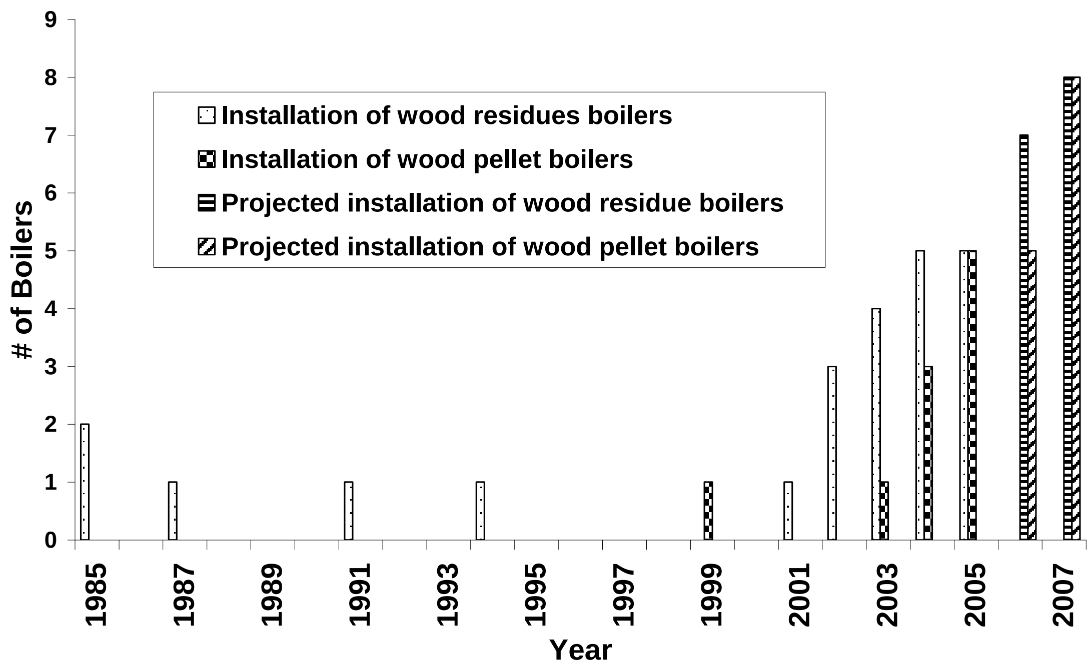

Figure 2.1. Annual installation of wood burning boilers in greenhouses in GVRD/FVRD. Adapted from (Melin 2006)

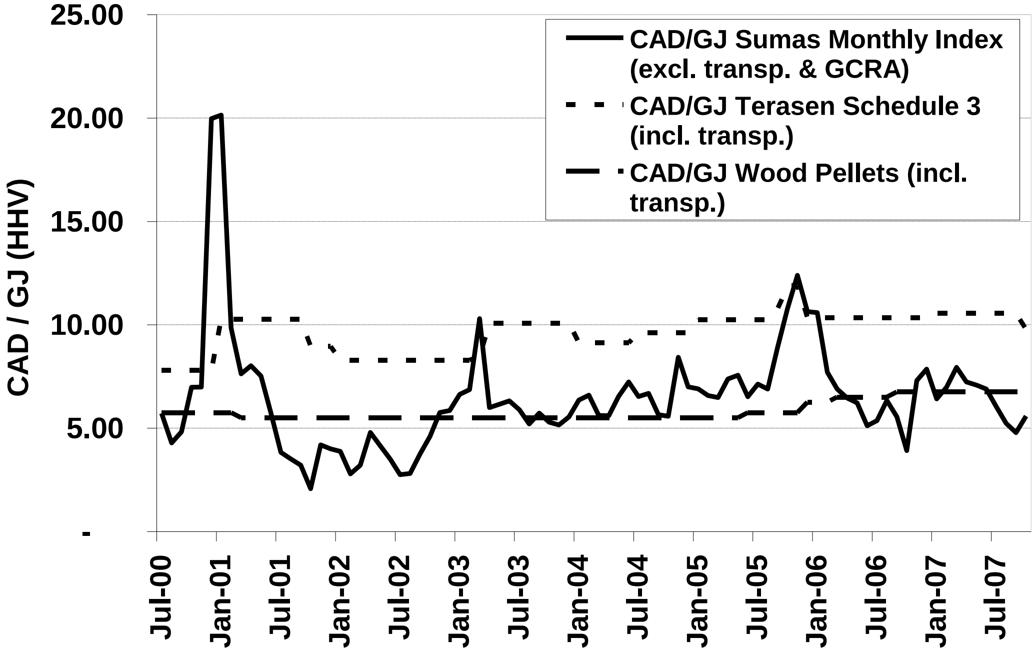

Figure 2.2. Historical prices of wood pellets and natural gas under contract by Terasen to users within GVRD versus the crossborder gas price at the U.S. Canada Border in Sumas, BC before delivery to users in BC. Adapted from (Melin 2007)

Although a lower biomass fuel price can generate savings for a greenhouse, the industry has some hesitations on converting to wood burning systems because of the high capital cost, the uncertainties regarding the long term availability of wood residue or wood pellets, and the emissions from combusting biomass.

Caputo et al. (2005) completed a detailed economic study on utilizing wood residue for producing electricity using combustion in comparison with gasification technologies in Europe. Using the net present value (NPV) method, they concluded that both technologies would generate profit for a 30 MW or greater plant over a 20 year project life. The biomass combustion system yielded a higher profit than a biomass gasification system due to capital cost. Sokhansanj et al. (2006b) investigated the cost of generating combined heat and power (CHP) from biomass (stover), coal, and natural gas for a 150 million L ethanol plant. The proposed CHP system required 137,450 Mg of biomass to generate 9.5 MW_e of power and 52.3 MW_{th} of process heat. Biomass fired CHP system generated an annual savings of C$3.61 million with a payback period of 6 years. Economics of the coal fired CHP system was more favorable than the biomass fired CHP system. But the greenhouse gas emissions from the coal fired CHP system were 20 times higher than that of the biomass fired CHP system. Sokhansanj et al. (2006a) used a dynamic simulation program to simulate the collection, storage, and transportation of agricultural biomass to a power plant. Depending upon the type of machinery and yield of biomass, the cost ranged from C$45 to C$75 per dry tonne (t) delivered to the power plant (60 km average distance).

A techno-economic assessment is a study of combining the technical and economical parameters which could affect the economics of a project. Most of the published literature is focused on the cost of logistics for transportation of biomass to a power plant and the advantages of one technology over another. However, there is only few studies focusing on the economic feasibility of using wood residue or wood pellets boilers for the greenhouse industry.

2.2 Objectives

The objectives of this research were to (1) develop a detailed method of analyzing the cost of heating a typical greenhouse; (2) apply the method to a typical commercial vegetable greenhouse in BC. The fuels studied were natural gas and biomass (loose forest residue or pelletized sawmill residue).

There are more than 85 commercial greenhouses in British Columbia (BCMAFF 2003). The size of a greenhouse ranges from 1 to 27 ha. This study investigated the techno-economic feasibility of installing a wood pellet or wood residue boiler in an existing greenhouse with an effective crop area of 7.5 ha that has a natural gas boiler already installed as the heat source representing an average sized greenhouse. The wood biomass system will provide 40% of the required heat, while the natural gas boiler will produce the remaining 60% of the heat and CO_2. Technical and cost information is required to perform a detailed techno-economic study. Information on heat and CO_2 demand, capital cost, installation cost, boiler systems efficiency, and labor and maintenance cost were gathered from literature and interviews with industry experts, boiler manufacturers and consulting engineers. Climate data from the Lower Mainland Region of BC (GVRD) were used. The assumed cost for equipment and labor were typical Canadian values.

2.3 Techno-economic factors

To evaluate the economic feasibility of a biomass boiler, one must take into the consideration greenhouse size and structure, boiler design, and type of fuels that influence the operating costs. Heat and fertilization with CO_2 are the two essential elements for vegetable crop production. Artificial light and supplemental nutrients were not considered in this analysis. The demand for heat and CO_2 vary with greenhouse location, crop type, and crop cycle.

2.3.1 Heat demand

Heat and ventilation are required to keep the greenhouse within a certain temperature range. On average, the temperature inside a greenhouse is kept between 16°C and 27°C (Nelson 1998) depending on greenhouse location, building structure, time of day, and type of crop. In order to determine the heat and fuel demand, one must consider the following factors:

2.3.1.1 Greenhouse structure

The amount of heat input to a greenhouse is determined by the heat loss due to conduction, ventilation, and radiation. Heat is mainly lost by conduction through the building materials such as glass, plastic, and aluminum frame (Nelson 1998). Equation 2.1 represents the overall heat demand for a greenhouse (ASAE 2003).

$$Q = UA(T_i - T_o) \tag{2.1}$$

where Q is the heat demand (W); U is the overall heat transfer coefficient (W/(m^2.°C)); A is the total cover area (m^2); and T_i and T_o are indoor and outdoor temperatures.

The overall heat transfer coefficient U represents heat losses due to various modes of heat transfer including conduction, convection, radiation, and infiltration. Equation 2.1 does not include the latent heat losses due to absolute humidity of the inside and outside air. These losses are small for moderate climates where the difference in absolute humidity of outside and inside of the greenhouse is not substantial and heat losses due to infiltration are small (ASAE 2003). ASAE EP 406.3 (2003) lists U values for greenhouses ranging from 0.6 W/(m^2.°C) for rigid acrylic material to a high of 6.8 W/(m^2.^{o}C) for single plastics and corrugated polycarbonate material. Most greenhouses in BC are constructed with glasses.

To size a heating system for greenhouses, ASAE Standard EP406.3 (2003) recommends to use the 99% winter design dry bulb temperature (99% of the time the temperature will be higher than a specified temperature). For Vancouver area ASHRAE (2005) specifies the 99% design temperature at -4.5^{o}C. The maximum design heating load should be based on the inside temperature required by the plants at night. A temperature of 16^{o}C generally meets the needs of most plants (2003). To maintain adequate temperature levels for photosynthesis, daytime temperature settings should generally be 6 to 11^{o}C higher than night time settings on bright sunny days and 3 to 6^{o}C higher on cloudy days.

2.3.1.2 Boiler system

Boilers can be classified by their fuel such as oil-fired, gas-fired, coal-fired, or solid fuel-fired boilers (Oland 2002). For example, biomass boilers are categorized as solid fuel-fired boilers whereas natural gas boilers are gas-fired. Boilers are also classified into fire-tube and water-tube boilers. In a fire-tube boiler, the combusted heat passes inside the tubes with fluid (water or oil) surrounding the tubes; whereas in a water-tube boiler, the fluid passes through the tubes with the combusted heat surrounding the tubes (Spring 1981). Greenhouses use water-tube boilers (natural gas-fired or biomass-fired), which are connected to a close-loop water system, to provide heat in the greenhouses. Hot water is circulated for heating purposes and returned to the boiler as cold or low-temperature water (Spring 1981).

Natural gas boilers are more commonly used in the greenhouse industry due to the relatively low capital cost in the range of C$10-C$30/kW (Oskarsson 1997) and their relatively small physical size. Moreover, burning natural gas can generate CO_2 for injection into a greenhouse. In contrast, biomass boilers are larger in size and have high capital cost (C$125 - C$166/kW) (Geletukha et al. 2000) due to more complex design. Unlike natural gas which is delivered by pipeline, wood biomass is mainly delivered by truck. Wood pellets are stored in a silo and wood residue is stored in flat storages in an open area or under a protected roof. The wood pellets are fed by auger into a burner and the wood residue by a combination of walking floor and auger. In addition to storage requirements, a larger area must be allowed for handling equipment between the fuel storage and burner's in-feed. Melin (2006) recommends roughly 50 m^2 of floor area for wood pellets and 200-300 m^2 of floor area for handling non pelletized biomass residues.

2.3.1.3 Boiler efficiency

The boiler efficiency is calculated as the ratio of energy output to the energy input. In 2004, the US Department of Energy (DOE 2004) promulgates new Federal energy efficiency and water conservation test procedures and related definitions for certain commercial and industrial equipment. Test procedures and efficiency standards, such as ASME PTC 4.1 and BTS-2000, for commercial packaged boilers (10 CFR Part 431) specify rules that manufacturers must use to certify their boilers efficiency and energy use (DOE 2004). For instance, the standard ASME PTC 4.1 (ASME 1974) provides a method of assessing and expressing boiler efficiency in terms of thermal efficiency, capacity and operating characteristics in a steam generator unit (Barroso et al. 2003, Covarrubias and Romero 2007, Ganapathy 1997). According to this standard, there are two methods to determine the boiler efficiency.

1. Input-output method

$$\text{Boiler efficiency} = 100 \text{ x } \frac{\text{Heat absorbed by working fluid(s)}}{\text{Heat in Fuel} + \text{Heat credit}} \tag{2.2}$$

2. Heat loss method

$$\text{Boiler efficiency} = 100\text{x}\left[1 - \frac{\text{Heat losses}}{\text{Heat in fuel} + \text{Heat credit}}\right] \tag{2.3}$$

The heat loss method is commonly used since one can identify the heat losses and increase the efficiency by improving the boiler's characteristics. For example, the radiation and convection loss for a boiler is dependent on the actual output and the air cooled wall factor (ASME 1974). Therefore, the boiler efficiency could be optimized by balancing the cooled wall structure and thereby the actual energy output. Heat losses could be due to incomplete combustion, high moisture content in fuel, high ash content in fuel, and inefficient boiler design. For instance, combusting high moisture materials requires energy to evaporate water in the fuel.

Some heat loss can be recovered by means of a flue gas condenser. Wood residue combustion is less efficient than wood pellets combustion because wood pellets have a consistently low moisture content of 5-7% (wet basis), whereas the moisture in untreated biomass residue may range from 10 to more than 50% (wet basis). With a lower efficiency boiler, the fuel demand is higher to satisfy the heat requirement.

2.3.1.4 Types of fuel

Natural gas is commonly used to generate heat and CO_2 for greenhouses. Natural gas has high calorific value (37 MJ/m^3; 55 GJ/t) and generates very small amounts of particulate matters when combusted (Boyle 2004). Wood residue and wood pellets are biomass fuels for greenhouses heating in BC. Wood residues, which includes wood chip, sawdust, planer shavings and bark/hog fuel, are primarily by-products from sawmills. British Columbia is the largest lumber producing region in Canada. Wood pellets are manufactured from sawmill residues. The heat content of biomass may range from 10 to 20 GJ/t depending upon the moisture content of the biomass. Ash content in biomass residue may range from a low of <0.3% in white wood pellets to 3-4% or higher in a mixed hog fuel (that may include bark).

In 2006, sawmills in BC interior produced over 6.5 millions dry t of wood residue which was about 31% of the total wood residue production in Canada (21 million dry t) (Bradley 2006). These materials are used to generate process heat or electricity within sawmills and are used for the pulp and paper process. Since wood residue is a by-product from lumber production, the price is relatively low. In order to use wood residue economically as a fuel, it is suggested that the transportation of wood residue should be within 200 km radius from the point of energy conversion (Natural Resources Canada 2006). The average moisture content of wood residue ranges from 20% to 60% and its net heat value is between 9 GJ/t and 17 GJ/t depending on the materials moisture content (Melin 2006).

Wood pellets are produced by compressing sawdust and shavings under high pressure in a pellet mill. The pellets are typically 6 mm in diameter with length varying from 6 to 24 mm in North America and have a specific density of 1200 to 1400 kg/m^3 and a bulk density ranging from 650 to 775 kg/m^3. Pellets have a rather consistent moisture content of 5-7% and are more suitable for transportation, storage, and combustion than other non-densified biomass products.

To produce one t of pellets, approximately 1.33 t of dry raw materials or 2.33 t of wet raw materials (50% moisture content) are required (Karwandy 2007). Since wood pellets are composed of wood residue, the chemical composition for wood pellets and wood residue are the same. On average, 40-50% of wood is cellulose, 20-35% is hemicellulose and 15-35% is lignin (Leaver 2006). Hemicellulose and lignin function as adhesive during the high temperature and high pressure pelletizing process.

The annual wood pellet production in BC was approximately 650,000 t in 2006 and the potential production in BC was estimated at 3 millions t (Melin 2006). Most of the wood pellets in BC are exported to European countries for heat and power production. While the wood residue supply could decrease due to weakening lumber markets resulting in shutdown of sawmills in BC, another source of biomass for wood pellet production is from the mountain pine beetle (MPB) infested trees. Since 1999, the volume of MPB infested trees in BC has increased exponentially and there were over 400 million cubic meters of infested trees in 2005 (Routledge 2006). A use for the MPB killed trees need to be found. Pelletization for fuel can be one use for the killed trees especially those at an advanced state of decay (Ministry of Forests and Range 2007).

The selection of boiler systems and fuel materials could lead to other capital investments. For instance, emission control system, such as baghouse, wet scrubber, and electrostatic precipitator (ESP), may be required to be added to a biomass boiler to reduce the particulate matter emissions. ESP is an advanced control system which effectively collects particulate matters from the combustion flue gas. However, the capital cost of such a system could be as high as $500,000 which may serve one or several boilers (Piejko 2007).

2.3.2 Carbon dioxide demand

Carbon dioxide in combination with water, heat and light is required for the photosynthesis process which produces carbohydrate for growth or maintenance of the plant (Langhans 1980). Equation 2.4 presents the synthesis of CO_2 to carbohydrates (Nelson 1998),

$$CO_2 + water + solar\ energy \rightarrow carbohydrate + oxygen \tag{2.4}$$

The CO_2 requirements of the plant vary continuously. Overall, CO_2 demand in summer is higher than during winter.

The current average CO_2 concentration in air is roughly 385 part per million by volume (ppmv) (Tans 2007) at sea level. With the increasing level of CO_2, scientists have found that there is a significantly increased growth of crops when the level reaches 1,500 to 2,000 ppmv (Nelson 1998) for vegetables. Aikman (1996) developed a procedure to determine the CO_2 enrichment of a greenhouse tomato crop in order to maximize the net crop yield and profit. The procedure includes the kinetics of crop growth, vegetable market price, weather prediction, ventilation, and other factors that may affect the CO_2 concentration in a greenhouse. Chalabi et al. (2002 a, b) applied this procedure and other similar studies to determine the optimal control strategies for CO_2 enrichment from the exhaust gas of natural gas boilers or alternatively liquid CO_2. Although the control strategies are different for the two CO_2 sources, the daily CO_2 concentration should be maintained between 1,000 and 1,500 ppmv during the daylight hours. However, there is no significant benefit with increased CO_2 concentration when growing flowers or bedding plants.

2.3.3 Source of CO_2

Carbon dioxide can be generated from natural gas combustion or can be purchased in liquid form. Pure natural gas produces heat, water, and CO_2 under complete combustion as follows (Boyle 2004),

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Energy \qquad (2.5)$$

A cubic meter of pure natural gas can produce 37 MJ of heat. Combustion of a GJ of natural gas produces approximately 50 kg of CO_2 (Naturalgas.org 2007). Typically, natural gas contains 95% of CH_4 and the generated CO_2 is generally considered by the greenhouse industry to be clean enough to allow direct injection into a greenhouse under complete combustion. Incomplete combustion of natural gas produces ethylene, which is highly phytotoxic, and carbon-monoxide (CO) that is extremely toxic to humans. Greenhouses install warning systems for CO to monitor the level of CO within the greenhouse. The combustion of natural gas also generates water which is typically removed by a flue gas condenser before the CO_2 is injected into the greenhouse as water causes fungus and mold in the greenhouses.

The wood pellets and wood residue considered in this study are composed of pure wood materials. Wood biomass that contains bark or impurity was not included as these materials generate high ash content and thereby high PM emissions. Combusting dry and clean wood biomass produces twice as much CO_2 as natural gas per input energy unit. Using the simple building block of cellulose, the main component of wood, a complete combustion of biomass can be represented as follows (Forest Products Laboratory 1999),

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + \text{Energy} \quad (2.6)$$

Biomass combustion does produce sufficient amount of CO_2 to reach 1,500 ppmv, but does not produce sufficiently clean CO_2 to allow direct injection into a greenhouse due to the variations in biomass quality and the generation of substantially more particulate matters. The flue gas from wood combustion mainly consists of PM emission and CO_2, methane (CH_4), and nitrous oxide (N_2O) (EPA 2003b), and is not suitable for the greenhouse crop production. It could be possible to capture clean CO_2 from biomass combustion; however, the research of such topic is in progress. Thus, vegetable greenhouses that are using biomass as a primary energy source purchase liquid CO_2 to enrich the greenhouse atmosphere. The cost of liquid CO_2 ranges from C$120 to C$200 per tonne of CO_2 (Melin 2006). For an average sized greenhouse (7.5 ha), the CO_2 demand could be roughly 2,400 t/y. This extra expense could decrease the attractiveness of wood biomass. Therefore, some greenhouses generate a partial of heat and CO_2 with natural gas boiler and the rest of the heat demand with biomass boiler.

2.4 Technical analysis

A techno-economic study was preformed based on a case study of a greenhouse in the Lower Mainland of BC corresponding to the average sized greenhouse. Table 2.1 lists input values for Equation 2.1 to calculate theoretical design heat power required for the 7.5-ha greenhouse. The resulting calculated heat value at 7.4 MW agreed well with the 7.5 MW natural gas boiler installed at the commercial 7.5-ha greenhouse. The greenhouse in this study obtains two 7.5 MW natural gas boilers which one of them provides 100% heat and CO_2, and another one functions as a backup for insurance purposes.

Table 2.1. Calculation of the heat power required for the 7.5 ha greenhouse

Parameter	Value
Greenhouse area (ha)	7.5
Greenhouse floor area dimensions (m)	274 x 274
Greenhouse height (m)	4.3
Covered area of greenhouse (m^2)	80,340
Overall heat transfer coefficient ($W/(m^2.^oC)$)	4
Design inside temperature (^oC)	16
Design outside temperature (^oC)	-4.5
Theoretical heat power requirement (MW)	7.4
Actual heat power specified for the 7.5-ha greenhouse (MW)	7.5

To calculate the annual heat demand, the average hourly temperatures for Vancouver for each of the 12 months were used. The temperature data used in this study were taken from the Department of Energy, US (2006). Equation 2.1 was expanded to calculate the monthly heat demand as follows

$$q_m = 3600 AU \sum_{j=1}^{12} N_j \sum_{i=1}^{24} (16 - T_{oi}) \tag{2.7}$$

where q_m is the monthly heat demand; A is covered area (m^2); U is overall heat transfer coefficient ($W/(m^2.^oC)$); N is the number of days in month j; and T_{oi} is the hourly ambient temperature averaged over the month.

Figure 2.3 plots actual and theoretical demands for natural gas for the 7.5-ha greenhouse. The theoretical demand using a midrange U = 4 $W/(m^2.^oC)$, which is used for the comparison between actual and theoretical heat demand, yielded almost half of the actual monthly natural gas use. When the monthly heat demand was recalculated using U = 8 $W/(m^2.^oC)$, the natural gas demands for months of November-March were in agreement with the actual recorded use of natural gas. This indicates that the actual natural gas use is much higher than the theoretical requirement for heating and that may be due to excessive heat losses (U = 8 $W/(m^2.^oC)$) for the existing greenhouses. The calculated heat demand for the remaining months were lower than the actual natural gas usage probably because most of the natural gas was burned in these months to meet the demand for CO_2.

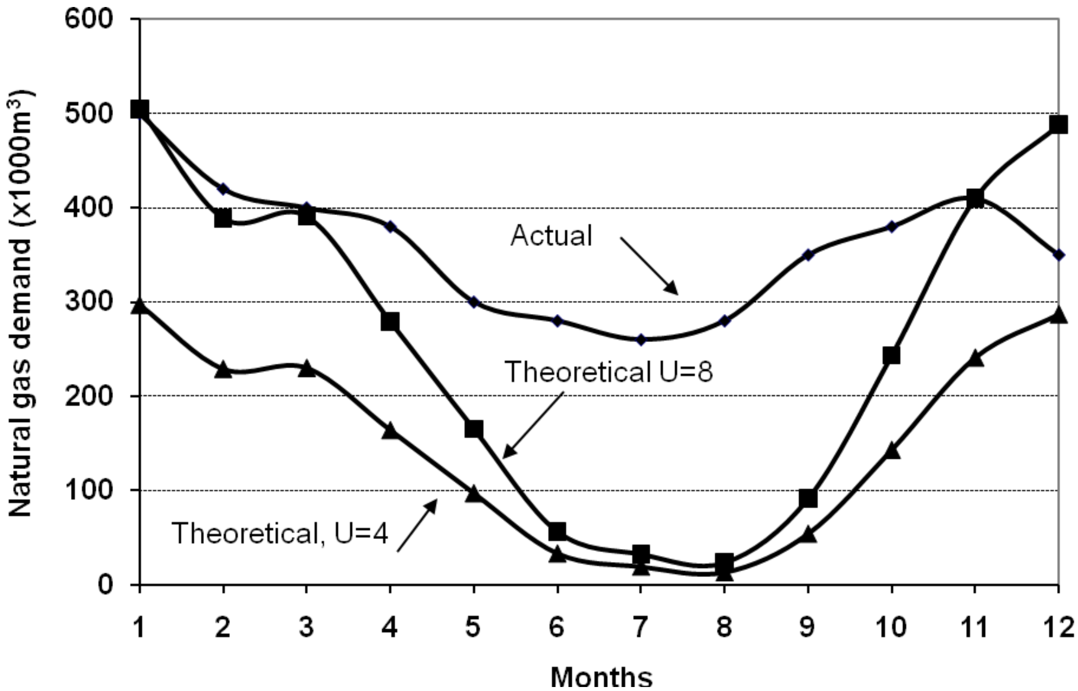

Figure 2.3. Monthly actual and theoretical heat demand for a 7.5-ha greenhouse. U is the overall heat loss coefficient (W/(m^2.^{o}C)). Natural gas heat value used was 37 GJ/m3. Actual heat demand data was collected from existing greenhouses

Based on a peak demand for a 24 hour period, a 5 MW biomass boiler was used in the modeling to cover 40% of the total annual heat demand while one of the natural gas boilers would provide 60% of the annual heat demand and CO_2. Figure 2.4 indicates the average monthly CO_2 in an average sized greenhouse. The demand was collected in the unit of GJ of natural gas combusted and was converted into ppmv using the following equation (Kamrin 1997),

$$ppmv = (\frac{mg}{m^3})\frac{24.45}{M_w} \text{ at normal temperature and pressure (NTP)} \quad (2.8)$$

where M_w is the molecular weight of CO_2 at 44 g/mol. The amount of natural gas used to generate this CO_2 demand accounts for approximately 30% of the total annual heat energy.

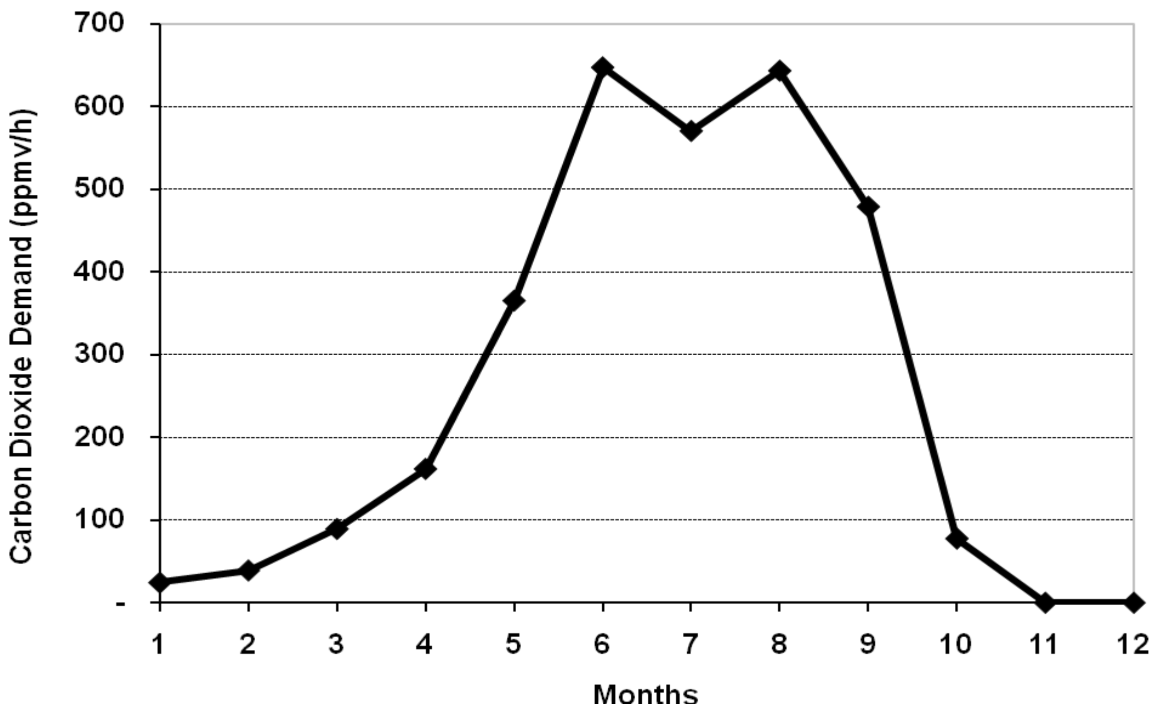

Figure 2.4. Average CO_2 concentration per hour in a 7.5-ha greenhouse by month

2.5 Economic analysis

The Net Present Value (NPV) is a method to evaluate the economics of a project. NPV is the sum of initial investment and the present value of all future cash flows at a particular discount rate. The cash flow of a biomass boiler includes initial investment, the annual operating costs, the annual debt payment, inflation, depreciable capital cost, and taxes. The NPV for different scenarios in this study were calculated using the engineering economics method from Eshbach (1990) and Hicks (1972) and the capital cost allowance guideline issued by Canada Revenue Agency (Garrison 2004). The capital cost of a natural gas boiler used as the back-up boiler system is irrelevant in the decision making (since it has been acquired in the past) and thus should not be included in this analysis. A major maintenance of $7,500 was applied to the natural gas boiler every 10 years. Further assumptions and information used in the analyses are listed in Table 2.2. The discount rate should be assigned by the company according to its financial objectives and tax strategies. An average general inflation rate of 2% (Statistics Canada 2007) was included in this study and discount rates of 5%, 10%, and 15% were used to determine the NPV for each scenario in the following analyses. The analysis does not cover a scenario consisting of a new greenhouse with a biomass boiler using liquified CO_2 for production of vegetables.

Table 2.2. Assumptions for engineering economic analysis

A projected energy inflation rate of 3% is selected for all fuel prices.	3%
An average general inflation rate (*f*) (Statistics Canada 2007)	2%
Portion of the initial capital and installation cost is provided by a bank loan	80%
Interest rate for loan	8%
Debt payment period (years)	10
Depreciation rate for equipment (Starky 2006)	30%
Depreciation rate for building (Starky 2006)	5%
Corporation tax rate (Canada Revenue Agency 2007)	38%
Equipment (boiler) service life (years) (Natural Resources Canada 2006)	25

2.5.1 Capital investment

Table 2.3 lists the initial investment of installing a 5 MW wood pellet and wood residue boiler. Both boiler systems consist of a boiler, fuel storage, infeed equipment, ash collection equipment, multicyclone, emission control equipment (Piejko 2007). The boilers in this study were assumed to be solid fuel-fired, water-tube boilers with vertical tubes configuration for the wood pellet boiler and with horizontal tubes configuration for the wood residue boiler. Each boiler includes a built-in multicyclone for capturing particulate matters; however, an ESP could be installed to further reduce particulate matters emission. Emission control devices such as external multicyclone and bag house could also reduce the particulate matters emission, therefore, the capital and operating costs of these devices could be considered in the economic evaluation. However, Metro Vancouver is proposing a new amendment on the Air Quality Management bylaw. When this bylaw is approved, a wood biomass boiler must be connected to an ESP system in order to satisfy the emission limits (Metro Vancouver 2008). Thus, an ESP system was selected for this study.

Table 2.3. Capital and installation cost of a 5 MW wood biomass boiler[a]

Description	Wood Pellet Boiler	Wood Residue Boiler
Boiler System [b]	C$1,490,000	C$1,450,000
Installation [c]	C$43,550	C$53,600
Land [d]	C$6,167	C$64,236
Feasibility Study	C$5,000	C$5,000
Electrostatic Precipitator	C$435,000	C$435,000
Crane Rental [e]	C$2,800	C$2,800
Building [f]	C$280,000	C$280,000
Miscellaneous	5% of the total above cost	5% of the total above cost

[a] The capital and installation cost of the natural gas boiler are irrelevant in this study
[b] The entire amount is depreciable at 30% Capital Cost Allowance (Starky 2006)
[c] A professional mechanical engineer costs C$33.50/h (Service Canada 2004). The total installation time is 1,600 h for wood residue boiler and 1,300 h for wood pellet boiler (Piejko 2007)
[d] Wood residue boiler requires about 10 times more land than wood pellets boiler as wood residue needs more space for storage. A greenhouse using wood residue boiler keeps a larger inventory than is required for a wood pellets boiler. The average agriculture land price in mid 2007 in the Lower Mainland is $220,000/ha.
[e] It requires approximately two days of unloading the machinery with crane. The rental cost for the crane is C$175/h
[f] Capital Cost Allowance for buildings depreciation is 5% per year (Canada Revenue Agency 2007)

2.5.2 Fuel requirement

Fuel demand is dependent on the boiler efficiency and the calorific value of the fuel. Due to different material properties, the boiler efficiency varies from 66% - 88% (Prasad 1995). Calorific value of the fuel is primarily determined by the moisture content. With moisture content of 5-7%, the wood pellet caloric value is about 18 GJ/t (Derketa 2003). The wood residue caloric value is 10.6 GJ/t at 40% moisture content (EIA 2007). Table 2.4 is a summary of biomass demand calculations and related fuel prices for different wood biomass boilers. The annual wood biomass demand is determined by Equation 2.9:

$$\text{Total biomass demand} = \frac{40\%\text{ of annual heat demand (GJ)}}{\left[\text{Boiler efficiency}\left(\text{decimal fraction}\right)\right]\left[\text{calorific value (GJ/t)}\right]} \qquad (2.9)$$

An actual annual heat demand of 163,611 GJ for a 7.5-ha greenhouse was used.

Table 2.4. Estimation of fuel requirement

Description	Wood Pellets	Wood Residue	Natural gas
Boiler efficiency (%)	88	66	92.5
Moisture content (%)	5	40	N/A
Calorific value	17.94 GJ/t	10.60 GJ/t	37 GJ/m^3
Total demand	4,147 t	9,355 t	2,868 m^3
Fuel price[a]	C$50-C$100/t[b]	C$20-C$60/t[c]	C$8.25/GJ
Total fuel cost (C$)	C$414,657	C$233,864	C$875,540

[a] Price includes purchase and transportation cost.
[b] C$100/t is selected as the wood pellet price in this study
[c] C$25/t is selected as the wood residue price in this study

2.5.3 Annual operating costs

Annual operating cost includes property tax/insurance, maintenance and spare parts, electricity, and other miscellaneous costs. A wood biomass boiler requires more labor and maintenance than wood pellets boiler. In general, the average annual operating and maintenance (O&M) cost of a wood residue boiler (C$75,000) is larger than that of a wood pellet boiler (C$10,000) as the wood residue ash content (2.5%) is higher than that of wood pellet (0.28%). In addition, biomass residue often contains serge material and other contaminants which may compromise the feeder system. Table 2.5 lists other annual costs for operating a wood biomass system.

Table 2.5. Estimation of annual operating costs of wood biomass boiler

Description	Wood Pellets	Wood Residue
Property taxes/Insurance	C$5,000	C$5,000
Spare parts	C$5,000	C$10,000
O&M labor	C$10,000	C$75,000
Contingencies	10% of the O&M	10% of the O&M
Fuel	C$414,657	C$233,864

2.6 Results and discussion

For the base case where a natural gas boiler was used to generate the total heat and carbon dioxide for the greenhouse, using the average natural gas price of about C$8.25/GJ (Terasen Gas 2007), the annual energy cost for a 7.5 ha greenhouse is C$1,459,234. The present worth of using a natural gas boiler for 25 years is -C$10.2 million at 10% discount rate. Four scenarios, listed in Table 2.6, were studied and the present worth of each scenario was determined.

Table 2.6. Scenarios used to supply heat to greenhouse[a]

Scenarios	Energy Sources[b]	Natural Gas Contribution	Biomass Contribution	Emission Control System[b]	
				Primary	Secondary
Base	NG	100%	--	Multicyclone	None
1	NG, WP	60%	40%	Multicyclone	None
2	NG, WP	60%	40%	Multicyclone	ESP
3	NG, WR	60%	40%	Multicyclone	None
4	NG, WR	60%	40%	Multicyclone	ESP

[a] The capacity of natural gas boiler and wood biomass boiler in the scenarios are 7.5 MW and 5MW respectively
[b] NG = Natural Gas; WP = Wood Pellets; WR = Wood Residue, ESP Electrostatic Precipitator

Figure 2.5 shows the NPV of each scenario minus the NPV of the base case at different discount rates. A positive NPV in this figure indicates the positive economics of using the selected system over the base case. Numbers in brackets (negative numbers) represent loss. The results indicated that using wood residue or wood pellets to produce 40% of the annual heat demand for an average sized greenhouse could recover the capital investment over the selected life span and selected discount rate. Wood pellets and wood residue boilers were acceptable at any discount rate except for wood pellets system with ESP at 15% discount rate. A lower NPV for pellets is due to the additional capital cost of the emission control system.

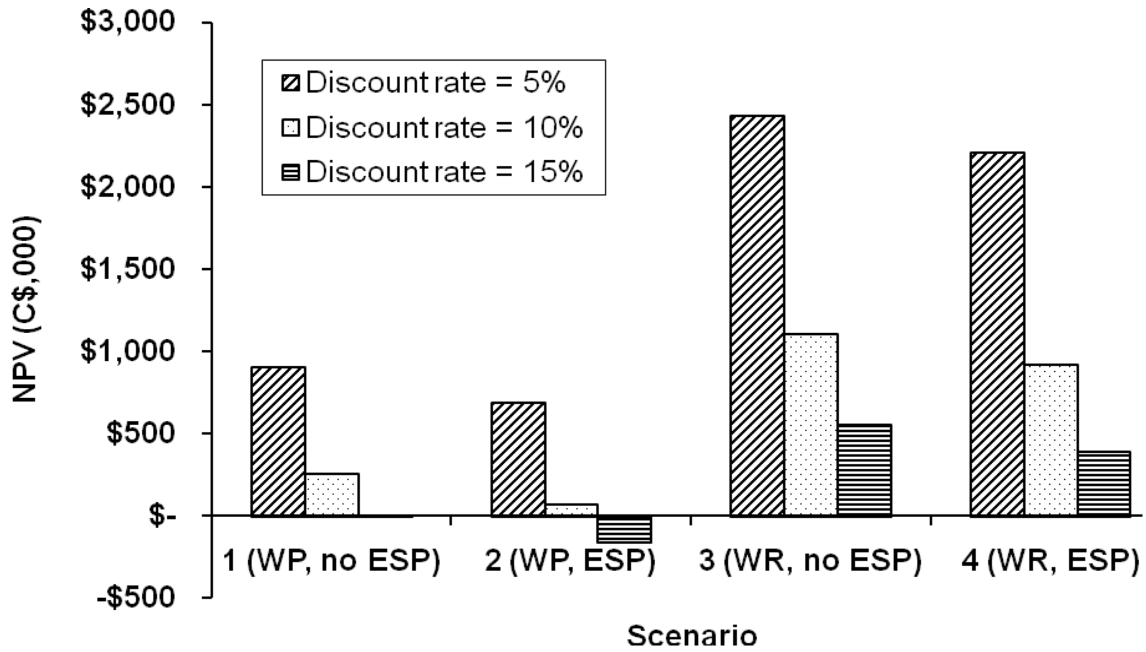

Figure 2.5. Summary of NPV for the wood biomass boiler at three discount rates

Using the emission factors for stationary combustion (EPA 2003a, IPCC 2006) and the amount of fuels combusted, the greenhouse gas emission and particulate matter emission for each scenario were estimated (Table 2.7). Using wood biomass boiler could reduce more than 3,000 t CO_2 equivalents of greenhouse gases (CO_2, CH_4, and N_2O) annually for each scenario, but more particulate matters and ash would be generated comparing to natural gas combustion. Particulate matter is a mixture of extremely small particles and liquid droplets suspended in the air (EPA 2007). The particle sizes range from 0.5 to 10.0 μm in diameter deposit in human's respiratory system causing irritation and other respiratory disease to humans (Smith 1987). Most particulate matters with diameter greater than 10.0 μm can be captured by a multicyclone filter. ESP can capture fine particles with diameter down to 2.5 μm or less. As a result, Scenario 2 and 4 (with an installed ESP as secondary emission control system) had a significant reduction of particulate matters emission. As of 2007, Metro Vancouver does not have a restriction for a facility which operates a biomass boiler to install an ESP. However, the proposing amendment of the Air Quality Management Bylaw requires a facility to install an advanced emission control system in order to meet the PM emission limit of 15 mg/m^3 (Metro Vancouver 2008). To ensure that the air quality within GVRD does not exceeds the Canadian ambient air quality standards, air quality monitors are located at different locations to measure the concentrations of various compounds. GVRD (2000) and BC Ministry of Water, Land and Air Protection - Water, Air, and Climate Change Branch (Wakelin and Rensing 2004) completed several emission inventory reports for the Lower Fraser Valley (LFV), with the values shown in Table 2.8. Measured emissions included sources from various industries, commercial and residential fuel combustion, transportation equipments, and other human or natural impacts. This table also indicates the percentage of emission contribution from each scenario compared to the emission inventory from the LFV. The emission contribution from each scenario would be less than 0.10% to the background inventory. The predictions in Tables 2.7 and 2.8 assumed complete combustion. Incomplete combustion could result in higher emission of greenhouse gases and particulate matters.

Table 2.7. Summary of GHG and particulate emissions

Scenarios	Carbon dioxide Equivalents (t)[a]	PM_{10} (t)[b]	$PM_{2.5}$ (t)[c]	Ash (t)
Base	9,947	0.1	0.1	0.0
WP, no ESP	6,529	8.7	5.2	11.6
WP, ESP	6,529	1.4	1.2	11.6
WR, no ESP	6,716	13.7	8.2	233.8
WR, ESP	6,716	1.8	1.6	233.8

[a] Main greenhouse gases include CO_2, CH_4, and N_2O. Gas emissions are converted to CO_2 equivalents

[b] Particulate matter less than or equal to 10 μm in diameter

[c] Particulate matter less than or equal to 2.5 μm in diameter

Table 2.8. Percentage contribution to the Lower Fraser Valley emission, by Scenario

Substance	Emission Inventory (t/y)[a]	Scenarios				
		Base	1	2	3	4
CO_2E[b]	25,356,950	0.043%	0.028%	0.028%	0.029%	0.029%
PM_{10}[c]	16,121	0.00088%	0.054%	0.0085%	0.085%	0.011%
$PM_{2.5}$[c]	7,947	0.0018%	0.065%	0.015%	0.10%	0.020%

[a] Emission inventory includes emission sources from various industries, fuel combustion, transportation, natural sources and human impacts.

[b] CO_2-equivalent emission inventory (including CH_4 and N_2O with global warming potentials of 21 and 310 times of CO_2 respectively) is based on measurement for the Lower Fraser Valley, BC (GVRD 2000)

[c] PM emission inventory is based on measurement for the Lower Fraser Valley, BC (Wakelin and Rensing 2004)

2.7 Conclusion

The objective of this study was to assess the techno-economic feasibility of using wood biomass for a greenhouse heating application. The NPV of a 5 MW wood pellet or wood residue boiler to provide 40% of the annual heat demand for a 7.5 ha greenhouse was evaluated and compared to that of a base case with a natural gas boiler providing 100% of heat demand.

Comparing theoretical heat demand and the actual heat supplied to a 7.5 ha greenhouse in Vancouver BC showed that the heat losses from the existing greenhouses are excessive. The techno-economic evaluation showed that installing a wood biomass boiler (wood pellet or wood residue) to provide 40% of the annual demand is preferable compared to a natural gas boiler to provide the heat demand assuming a discount rate of 10%. For an assumed lifespan of 25 years, a wood pellets system could generate NPV of C$259,311 (without ESP) and C$74,695 (with ESP). Installing a wood residue boiler with or without an ESP could provide NPV of C$919,922 or C$1,104,538, respectively. Using a wood biomass boiler could reduce over 3,000 t of CO_2 equivalents of greenhouse gases annually. Wood biomass boilers generate a higher volume of particulate matters (PM) and ash emissions than natural gas. An installed ESP can efficiently reduce the PM emission from the wood biomass combustion flue gas resulting in the similar level as natural gas. Although adding an ESP will increase the capital investment by approximately C$500,000, the positive NPV results indicated that the installation of ESP did not affect the feasibility of a wood biomass boiler at a discount rate of 10%.

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Chapter 3. The Impacts of Technical and Market Changes on the Economics of Wood Biomass Utilization for Heat Generation for the Greenhouse Industry

3.1 Introduction

Greenhouse operators have been facing increases in price of natural gas to provide heat and CO_2 to their greenhouse. To cope with this high natural gas price, operators have been installing alternative fuel sources, especially biomass and other solid fuels to supply heat to boilers. Biomass is a renewable resource that is greenhouse gases (GHG) neutral when converted to heat energy properly. The existing biomass burners often encounter problems with severe fouling and occasionally undesired emissions (Broek et al 1995). The problem can be traced to the quality of biomass used in the burner/boiler system. It is known that a wet biomass with variable particle size and high impurities would result in a larger biomass burner, poorer energy plant operation and higher maintenance costs. The security of supply and fluctuations in price and quality add to uncertainties in biomass as a dependable and predictable source of fuel for the industry. Although a survey from Delta Research Corporation (Melin 2006) predicted that the price of wood pellets would be steady for a number of years, the growing demand of wood residue and pellets could increase the price of wood biomass.

Government investment incentives and emission taxations are other factors that could affect the economical feasibility of a biomass project. To show the benefits of these financial supports, sensitivity analyses are usually included in the economic study. De Lange and Barbucci (1998) determined that the project of generating electricity by a 10.9 MW integrated gasifier with a mixture of wood chips and forestry and agricultural residues, when 37% of the total investment cost was subsidized, would provide an acceptable rate of return to the shareholders within five years. With more than 50% investment grants, the heat provision cost in Germany would be reduced to 12.9 €/GJ (for wood chips supported system) from 14 €/GJ (for fossil fuels supported system) (Schneider and Kaltschmitt 2000). In addition to the subsidy, applying CO_2 tax on fossil fuel would increase the competitiveness of wood chips by reducing

* A version of this chapter has been submitted for publication. Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S. and Bi, X (2008) The impacts of technical and market changes on the economics of wood biomass utilization for heat generation for the greenhouse industry. Applied Energy

22% of the heat provision cost from fossil fuels. Sundberg and Henning (2002) did a similar analysis and determined that a CHP plant was profitable with the electricity price increased more than 40% of the average price of 192 SEK/MWh, or with governmental grants and emission taxation applied.

Chapter 2 analyzed the economic feasibility of installing wood biomass (wood pellets and residue) boilers to cover 40% of the total heat demand in an existing average-sized greenhouse located in Greater Vancouver Regional District (GVRD). However, the chapter did not include variations in economic factors and sensitivity of cost/benefit to the changes in system and fuel costs. Sensitivity analysis is necessary to reduce the risk of a change from natural gas to biomass.

3.2 Objective

The objective of this research is to study the impacts of fuel price, energy contribution, and boiler capacity, on an economic indicator (NPV) of producing heat for a greenhouse using natural gas and wood biomass.

3.3 Background

Most of greenhouses in British Columbia (BC), Canada consume natural gas to generate heat and CO_2 for crops production (Melin 2006). Chapter 2 investigated the feasibility of installing a biomass boiler in an average-sized greenhouse with an effective crop area of 7.5 ha. The study considered four scenarios (Table 2.6): a wood pellet boiler or a wood residue boiler, each with or without an electrostatic precipitator (ESP) for particulate matters control. The biomass boilers were equipped with a basic cyclone for primary dust collection. Wood pellets are produced from saw dust and shavings from sawmills along Fraser River and BC Pacific coastal mills. The pellets have a specific gravity of 1.2 and a bulk density of 650 kg/m^3 (Mani et al. 2006). The moisture content of pellets is about 6% (wet basis, wb) with an ash content of less than 0.5%. Wood residues are mostly loose biomass from mill residues containing pieces of bark and low quality wood chips. The bulk density ranges from 100-200 kg/m^3. The moisture content of the wood residue varies from a high of 50% wb to a low of 10% wb. The ash content is unknown, but may vary as some of the fuel may contain dirt and other impurities.

The economic analysis in Chapter 2 considered the differences in fuel quality, in the price and the heating value of the fuel. Table 2.4 lists the characteristics of fuels, thermal efficiencies of wood pellets and wood residue boilers, and the price of raw material for a 5 MW wood biomass boiler. For each scenario, 40% of the total heat demand was provided by wood biomass boiler system, with the remaining heat and CO_2 demand to be provided by the existing natural gas boiler. The analysis used the net present value (NPV) method and the capital cost allowance guideline by Canada Customs and Revenue to conduct a cost benefit analysis for using wood biomass boilers. The average heat demand for a greenhouse in Vancouver area of BC was calculated to be 21,815 GJ/ha. This calculation was based on the outdoor temperature in Vancouver area that stays above -4.5^{o}C 99% of the time (ASHRAE 2005).

As most greenhouses in BC have at least one natural gas boiler, CO_2 demand is satisfied by the existing natural gas boiler; thus, the purchase of additional liquid CO_2 cost was not included in our study. Table 2.2 and 2.3 list the initial capital expenditures and other financial assumptions applied in the economic study. The fixed capital costs for a 5 MW biomass boiler installation were slightly lower for the pellet boiler than the residue boiler. Pellet boiler requires less storage space (due to higher bulk density) and less material handling equipment due to its ease of handling.

3.4 Sensitivity analysis

Three sensitivity analyses are performed based on the case studies in Chapter 2. The analyses determine the impact of the changes in fuel prices, wood biomass contribution to heat demand, and greenhouse size.

3.4.1 Fuel price

The natural gas price used was C$8.25/GJ with a heat value of 38.6 MJ/m^3. This price is relatively high compared to that of wood residue (C$2.36/GJ at 10.60 GJ/t) and that of wood pellets (C$5.57/GJ at 17.94 GJ/t). These low biomass prices (in comparison with natural gas), however, only apply when the material supply is secured and there is no price effect due to rapid growth of biomass demand which creates supply shortage. Unstable supply and fuel price volatility are two factors important in biomass projects (UNEP 2004). Wood residue was formerly hauled at no charge. With the increasing demand of wood pellets production, for which wood residue is the raw material, the fuel cost has increased overtime (Bradley 2006). Greenhouses in BC consume approximately 12,500 t of wood pellets annually (Melin 2006). If all greenhouses in BC convert to wood biomass boilers, wood biomass price will increase due to the growing biomass demand. The increase in fuel price can be represented by the following equation

$$FC_n = FC_1 * (1 + f_p)^n \tag{3.1}$$

where FC_n is the fuel cost in year n, f_p is annual increase rate, and n is year. FC_1 is fuel cost in year 1.

Equation 3.1 shows that the initial wood pellet price at C$100/t will increase to C$138/t after 10 years if the annual rate increased by 10% from the base case of 3% per year.

Wood pellets are a more expensive material than wood residue as pellets require extra processes and transportation. As a result, wood pellets have less flexibility to change in terms of price inflation. Figure 3.1 shows the impact of changing wood biomass annual increase rate on the NPV of the wood biomass project. While the NPV of each scenario decreases as the wood biomass inflation increase, the projects are still economically feasible with positive NPV. The capital cost of ESP further decreases the flexibility of wood pellet price and results in a negative NPV of C$80,000 when the wood pellet annual increase rate is 20% higher than the base case. On the other hand, the relatively low wood residue price ensures the project feasibility with the changes in price. Wood residue boiler, with or without ESP system, generates positive NPV of C$1,014,000 and C$829,000, respectively, with 20% increase of the wood residue price inflation (Figure 3.1).

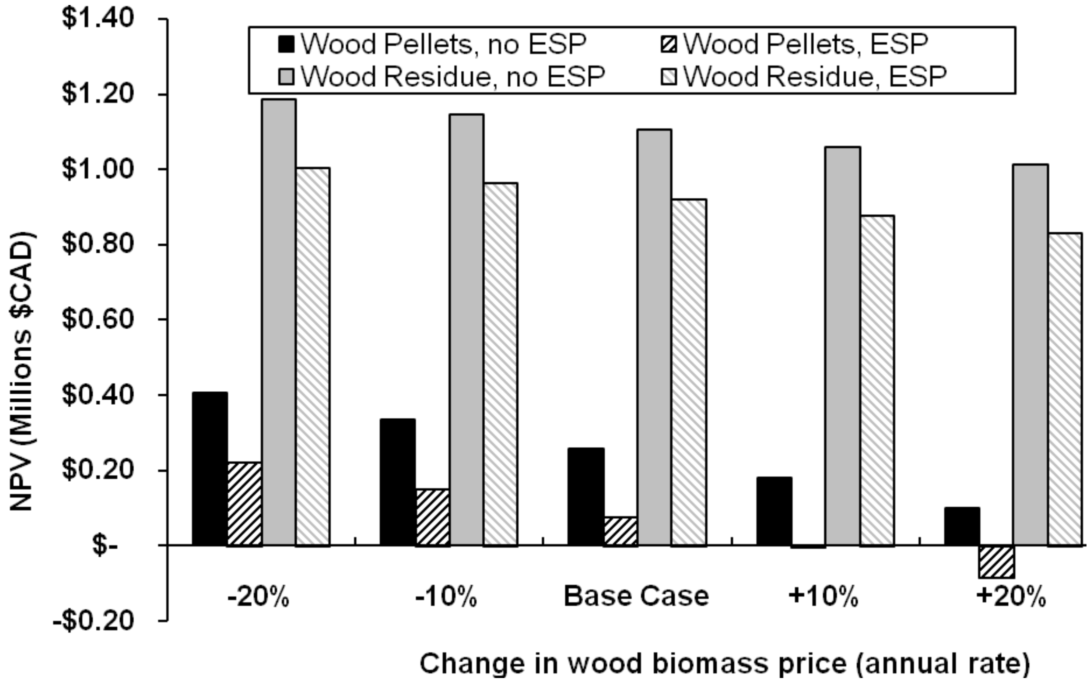

Figure 3.1. NPV of wood biomass boilers at changing annual inflation rates for fuels and with a fixed rate of 3% inflation rate for natural gas

The world natural gas demand is projected to increase by 1.9% per year, and 0.5% to 0.7% per year in Canada (EIA 2007). Thus, the fuel price is unlikely to be stable for the next few years. Biomass becomes a competitive alternative energy source because of the cost saving created by the price difference. Any change in wood biomass or natural gas price will affect the attractiveness of these projects. Figure 3.2 shows that installing wood pellet and wood residue boilers become more attractive with higher natural gas price changes. For instance, a 10% growth of natural gas inflation to 3.3% per year for a lifespan of 25 years will increase the NPV of wood pellet boiler to C$350,000 or C$534,000, with or without ESP, respectively. Wood residue boiler (regardless of ESP) is economically attractive with any changes applied on natural gas inflation. However, wood pellet boiler becomes non-economic with 10% or greater decrease in natural gas inflation rate. According to a recent EIA's report (EIA 2008), the average natural gas price in the US will increase by 7.9% to more than US$13.32/mcf (US$0.470/m^3) in 2008. The growth of natural gas price rapidly increases the wood biomass competitiveness.

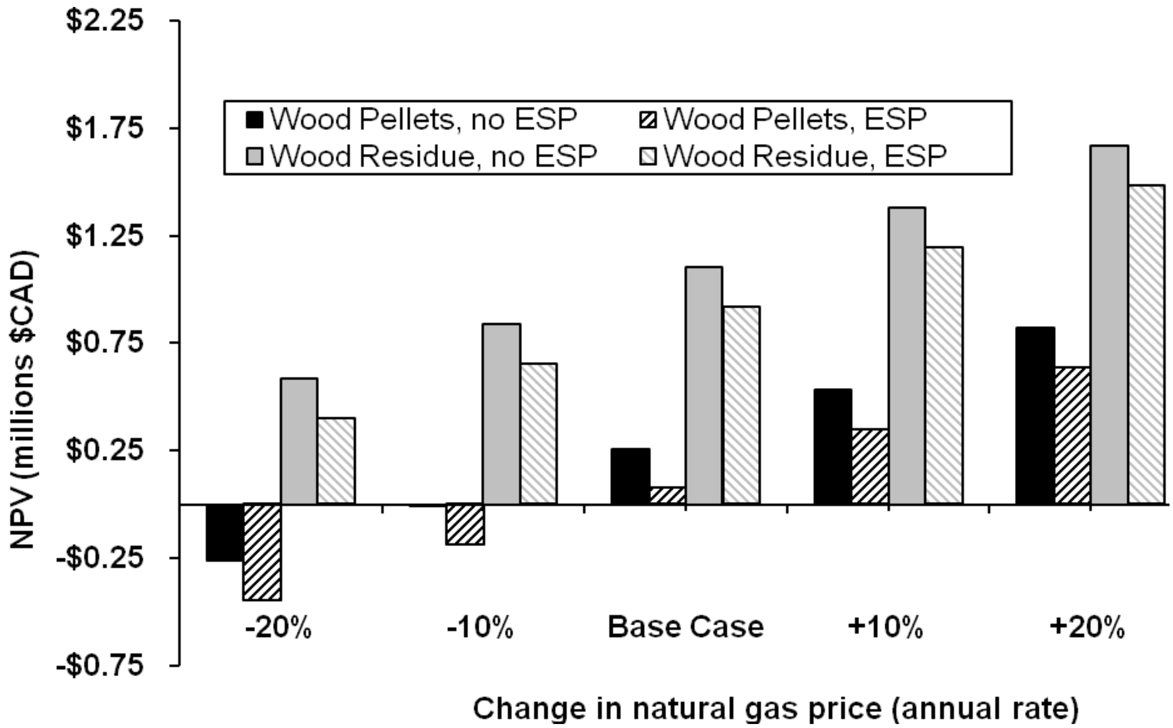

Figure 3.2. NPV of wood biomass boilers as a result of change in the natural gas inflation

3.4.2 Biomass contribution to heat demand

The CO_2 concentration in a vegetable greenhouse space is maintained between 1,000 and 1,500 ppmv to enhance the crop growth (Nelson 1998). The CO_2 can come from two sources: CO_2 enriched flue gas from natural gas combustion or from capsules filled with liquid CO_2. The greenhouse industry considers natural gas combustion as a clean process and thus safe to inject the flue gas directly into a greenhouse space. On average, CO_2 demand is approximately 30% of the total heat demand (for 37.5 kg/(ha·h) of CO_2 enrichment, provides about 1,500 ppmv = 0.75 GJ of natural gas) (EECA 2005). A natural gas fired boiler that meets the heat demand of the greenhouse often produces more CO_2 than required. For the 7.5-MW natural gas heating system in Chau et al's (2007) roughly 60% of the total heat demand is satisfied by natural gas boiler. The flue gas produced was used to support the CO_2 demand. Thus, liquid CO_2 was not required.

Liquid CO_2 is purchased when the wood biomass boiler contribution to heat demand is greater than 70%. Based on 30% of the total heat demand for a 7.5 ha greenhouse and a conversion factor of 50 kg of CO_2/GJ of natural gas combusted, the supplementary liquid CO_2 demand is about 2,437,324 kg. Table 3.1 lists the liquid CO_2 cost and the annual fuel cost for a 7.5 ha greenhouse based on biomass boiler contribution to heat demand. When liquid CO_2 is used, the extra cost of C$300,000 per year reduces the attractiveness of wood biomass by C$2.7 millions in NPV (25 years of C$300,000 annuity discounted at 10%).

Table 3.1. Annual liquid CO_2 and fuel cost based on biomass boiler contribution

Biomass contribution (%)	Liquid CO_2 cost[1] ($)	Annual fuel cost[2] ($)		
		Natural gas	Wood pellet (Scenario 1 & 2)	Wood residues (Scenario 3 & 4)
10	--	1,313,311	103,664	58,466
20	--	1,167,387	207,328	116,932
30	--	1,021,464	310,992	175,398
40	--	875,540	414,657	233,864
50	--	729,17	518,321	292,330
60	--	583,694	621,985	350,796
70	--	437,770	725,649	409,261
80	304,665	291,847	829,313	467,727
90	304,665	145,923	932,977	526,193
100	304,665	--	1,036,642	584,659

[1] The average liquid CO_2 price is $0.125/kg

Figure 3.3 shows that economics of wood biomass heating system depends upon the change of biomass share in heating the greenhouse. The share of biomass boiler to generate heat must be more than 30% (or 10% less than the base case) in order to achieve a positive NPV for wood residues, while it has to be more than 40% (at the base case) for wood pellets. With an additional 20% of heat demand supported by wood biomass boiler (to 60% contribution rate), a wood residue system generates about C$2.3 millions over the service life of 25 years, while a wood pellet system generates around C$750,000.

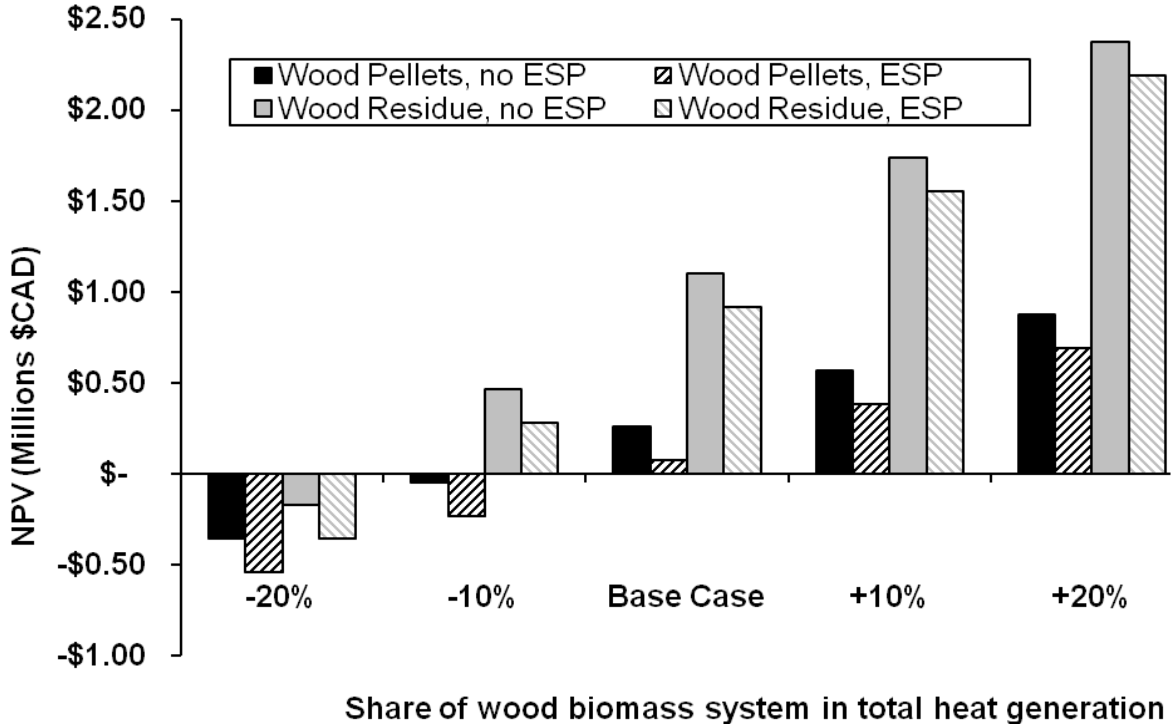

Figure 3.3. NPV of wood biomass heating systems based on change of heat demand contribution at 10% discount rate

3.4.3 System capacity

An existing average-sized greenhouse uses a 5 MW wood biomass boiler to generate partial heat demand; the estimated annual heat demand for Vancouver climate is 21,815 GJ/ha. Equations were developed in Chapter 2 to predict the power (heating power) and the annual heat demand based on the recommended design ambient temperature of -4.5^{o}C and inside greenhouse temperature T=16^{o}C. The optimum temperature inside a greenhouse is set at T=21^{o}C, an average temperature in the existing greenhouse. To calculate the heating power (boiler size) and the annual heat demand, a value of overall heat loss (U) for the greenhouse is required. Using the 5 MW wood biomass boiler for 7.5 ha and T=16^{o}C will require U= 3.1 W/(m^{2}.^{o}C). Using the 21,815 GJ/ha for the annual heat demand and T=21^{o}C will require U=5.8 W/(m^{2}.^{o}C). Most of the greenhouses in BC are constructed with glass, for which the heat loss coefficient is 5.4 W/(m^{2}.^{o}C) (single glass, low emissivity) or 6.2 W/(m^{2}.^{o}C) (single glass, sealed) (ASAE 2003).

Table 3.2 lists the designed size of boilers (in MW) and the annual heat demand for the two cases of a low heat loss and low temperature and a high heat loss and high inside temperature. For an average-sized greenhouse (7.5 ha) the designed size of the boiler can range from 5 to 11.7 MW with the corresponding heat demand ranging from 48,180 GJ to 163,608 GJ. The boiler for a small greenhouse (3 ha) can range from 2.1 to 4.9 MW; boiler for a large greenhouse (15 ha) ranges from 9.8 to 23.1 MW. Since the wood biomass boilers are designed to satisfy 40% of the total heat load, the boiler size used in the sensitivity analysis is according to the low heat loss and low temperature case (U= 3.1 W/(m·^{o}C), T=16^{o}C).

Table 3.2. Designed boiler size and annual heat demand for various foot print area of a greenhouse

Size (ha)	U=3.1, T=16		U=5.8, T=21	
	Power (MW)	Heat (GJ)	Power (MW)	Heat (GJ)
Small (3.0)	2.1	19,929	4.9	67.674
Average (7.5)	5.0	48,180	11.7	163,608
Large (15.0)	9.8	94,704	23.1	321,597

U= Overall heat loss, $Wm^{-2o}C^{-1}$,
T= Inside greenhouse temperature (^{o}C)

Piejko (2007) predicted the boiler system capital cost to increase by 20% with an additional megawatt of capacity. The Perry's Chemical Engineering Handbook (Perry et al 1997) recommends the power law rule to extrapolate from the cost of one size capital equipment to another size of the capital equipment,

$$C_{new} = C_{base}\left(\frac{P_{new}}{P_{base}}\right)^{n} \quad (3.2)$$

C_{new} and C_{base} stand for the new cost and base cost. P_{new} and P_{base} stand for new power and base power. The power factor n is upon the type of equipment and capital expenditure. Combining the 20% value proposed by Piejko (2007) and Equation 2 suggests that a value of n=0.47 has a best fit.

Figure 3.4 illustrates the NPV of a wood biomass systems based on three greenhouse sizes. From a purely economic standpoint, as the size of greenhouse increases, a wood residue boiler becomes a less expensive choice compared to a wood pellet boiler. For larger greenhouses such as a 15 ha greenhouse, a wood residue boiler with and without ESP obtains a positive NPV of C$2.6 millions and C$2.8 millions, respectively, while a wood pellet boiler system with and without ESP only generates, C$600,000 and C$780,000 NPV, respectively. Wood biomass boiler is not economically feasible for a small greenhouse as the small saving from natural gas is not enough to cover the capital cost of wood biomass boiler. Nevertheless, a wood residue boiler without an ESP system could be installed in a small greenhouse with a positive NPV of C$75,000 within the assumed lifetime of 25 years.

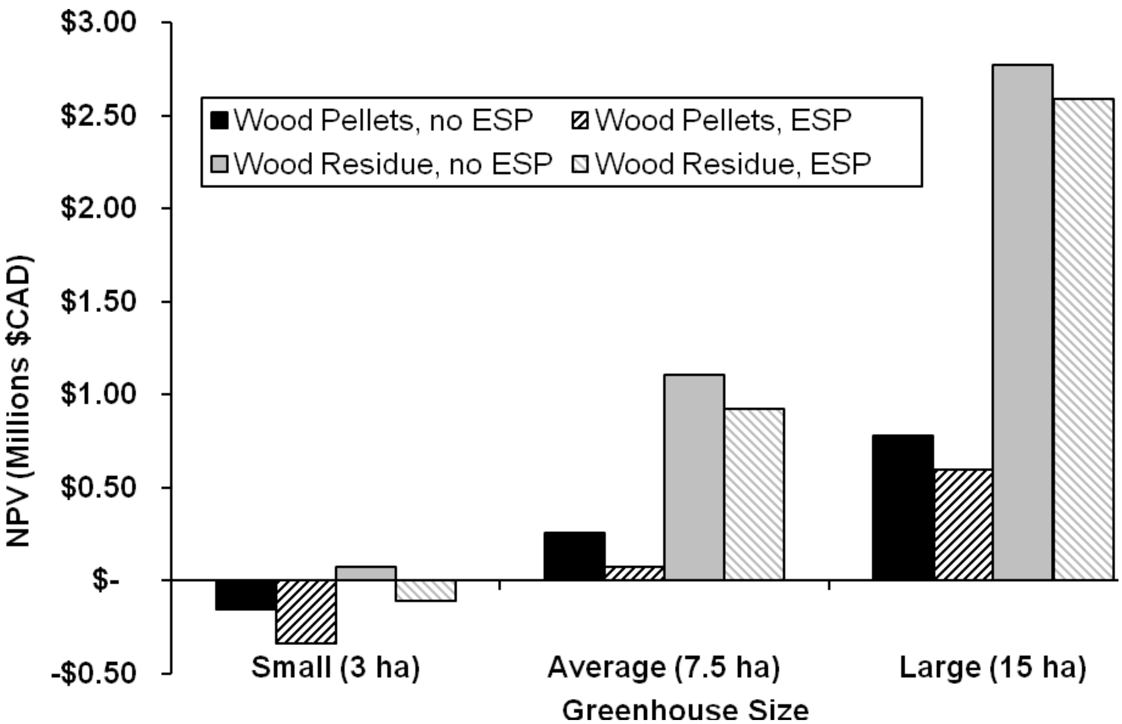

Figure 3.4. NPV of wood biomass boilers based on different sizes of a greenhouse and calculated at a 10% discount rate

3.5 Conclusions

The objective of this paper was to study the impact of fuel price, energy contribution by wood biomass boiler, and greenhouse size changes on the profitability of installing a biomass fuel boiler. The base case was a 7.5 ha greenhouse located in Vancouver BC area requiring 5

MW heating power of biomass boiler to cover 40% of the total heat demand. In general, the increase of wood biomass inflation rate slightly decreases the NPV of the projects. If the wood pellets inflation rate increased by 20%, wood pellet boiler with an ESP system will not be economically feasible as the NPV will be negative. On the other hand, installing a wood biomass boiler will be feasible when natural gas price increase more than 3% per year (base case). With the growing demand of natural gas, the natural gas price is expected to rise. In addition, if Canada deploys carbon taxation or restrictions on fossil fuels, the total cost of fossil fuel will increase significantly which creates a more favorable market for wood biomass. To obtain the feasibility of wood biomass boiler, wood pellet boiler should contribute at least 40% of the total heat demand, while wood residue boiler should support at least 30% of the heat demand. A greenhouse can be fully supported by a wood biomass boiler. However, the extra liquid CO_2 cost will reduce the project's NPV by C$2.7 millions which may not be economically feasible. In terms of greenhouse size, wood residue boiler has a higher NPV than wood pellet boiler at any greenhouse sizes. Installing a wood pellet boiler is not economical for a small greenhouse (3 ha) as the NPV becomes negative. Nevertheless, wood biomass boiler is suitable to generate 40% of the total heat demand for an average (7.5 ha) or a large (15 ha) greenhouse for a lifespan of 25 years.

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Chapter 4. Optimizing the Mixture of Wood Biomass for Greenhouse Heating

4.1 Introduction

The Canadian vegetable greenhouses generated more than C$827 million revenues in 2006, while the total sales of flower greenhouses were C$1.52 billion (Statistic Canada 2007). Approximately 21% of the total flower sales and 30% of the total vegetable sales were in British Columbia (BC), a province in Canada. The greenhouse industry in BC has grown significantly since 1993 and has created 8,490 FTEs (Full Time Equivalent) in 2002 (BCMAFF 2003).

Vegetable and flower greenhouses require heat and carbon dioxide (CO_2) to enhance crops productivity. Natural gas is the primary fuel for generation of heat and CO_2 for crop enhancement for the greenhouse industry in BC. The heat and CO_2 requirements are lower for a flower greenhouse compared to that for a vegetable greenhouse; the exact amount of required heat and CO_2 depends on types of crops and greenhouse location (Nelson 1998). For instance, orchid production requires indoor temperature of 11^{o}C with no CO_2 enrichment. Therefore, no flue gas from natural gas combustion is injected in an orchid greenhouse. Although natural gas is one of the cleanest fossil fuels, natural gas combustion emits fossilized carbon and other greenhouse gases to the atmosphere. With the raise of natural gas price and environmental concerns, the greenhouse industry in BC is converting to wood biomass heating systems.

Wood biomass combustion does not affect the overall CO_2 inventory as the carbon released from wood combustion equals the average carbon absorbed during natural biomass regeneration. Nevertheless, there are concerns about other emissions at the biomass combustion site. Particulate matter (PM) is an air contaminate of most concern since it causes irritation and respiration infection to humans (Smith 1987). The PM emission is higher from wood combustion than that of natural gas, assuming complete combustion. Therefore, advanced emission control systems are required to reduce the PM emission from biomass combustion. In addition, flue gas from wood combustion cannot be injected into greenhouses for CO_2 enrichment as the toxicity of the generated CO_2 is uncertain at this point. Thus, most of the

* A version of this chapter has been submitted for publication. Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S. and Bi, X (2008) Optimizing the mixture of wood biomass for greenhouse heating. International Journal of Energy Research.

greenhouses continue to use natural gas to generate CO_2. An alternative CO_2 supply is to purchase liquid CO_2.

There have been an increasing number of greenhouses converting to wood biomass boilers (Melin 2006). Depending on boiler design and economics of fuel supply wood residues (wood chips and sawdust from sawmills) or wood pellets (densified wood residues) may be utilized to provide heat for greenhouses. Wood residue is a relatively low cost material. This material is often high in moisture content (over 50%) and low in calorific value (range from 10 to 20 GJ/t). Wood residue also has high ash content (2.5%) due to the material impurity and increased ash content in the bark component. Wood pellets are more consistent in terms of physical size and material properties (4% moisture content with 18GJ/t of heat value). However, wood pellets cost more than wood residues, approximately C$100 to C$120 per tonne (t) delivered to greenhouses located in the Lower Mainland of BC.

Provided a boiler can accept both wood residues and pellets (a boiler only accommodates the materials specified by the manufacturer), an optimum amount for each fuel type can be estimated in order to minimize the total operating cost of biomass combustion. Linear programming (LP) model is a widely used methodology to solve these optimization problems. Other LP applications include biomass production planning, transportation scheduling, and financial decision making. Cundiff et al. (1997) formulated an LP model to minimize the transportation cost and the storage expansion cost from various on-farm storages to a fuel ethanol plant in the Piedmont of Virginia. The problem was solved with the CPLEX linear programming solver; the estimated total delivered cost ranged from $13 to $15/dry Mg for a distance within a 50 km radius around the fuel ethanol plant.

Linear programming technique has been used in many other resource allocation applications. Examples of such applications in production planning and scheduling are described in (Sartori et al 2001, Sartori and Florentino 2007). Sartori et al (2001, 2007) developed an LP model to maximize the energy yield during the production and transportation of sugarcanes. The LP model was able to estimate the yield of various types of sugarcane planted in the selected area based on factors such as sugarcane energy contents, area limitations, and harvesting methods.

Other than production planning and scheduling, linear programming has also been utilized to estimate an optimal fuel mix. Nienow et al. (2000) formulated a mathematical model to find the optimal amount of biomass and coal for co-firing in order to minimize the total operating cost and to satisfy the technical and emission constraints. The model considered material properties, emission properties and biomass supply requirements. The results showed that using a mixture of low cost waste wood ($1.80/Mg), willow ($14.50 – $21.65/Mg), and coal ($17.30 – $33.25/Mg) to produce electricity would yield a minimum generated electricity cost compared to using coal only.

The purpose of this paper is to determine the optimal fuel mix of wood pellets and wood residue for generating heat for a two hectares (ha) flower greenhouse and a 7.5 ha vegetable greenhouse, both located in the Lower Fraser Valley (LFV) of BC, Canada. The developed LP model determines the optimal amount of wood pellets and wood residues in order to minimize the annual total cost and to satisfy the emission limits and other constraints such as resources availability and technologies requirement. In this model, it is assumed that CO_2 demand is satisfied by liquid CO_2 or natural gas combustion, and the heat generated by natural gas is not applied to the greenhouse. A sensitivity analysis is also performed in order to identify the uncertainties related to parameters and limitations.

4.2 Model structure

4.2.1 Decision variables

Decision variables (X_i) in an LP model are mathematical symbols that represent a possible level of production or operation (Russell and Taylor 2000). A feasible optimal solution of an LP model is a set of decision variables that generates the best solution to a problem while satisfying defined constraints. A decision variable can be an integer, a continuous value, or a binary variable (1 or 0). All decision variables should be non-negative values. Thus, a non-negative constraint on the decision variable is added in an LP model. In our model, the decision variables are defined as the amount of wood pellets and wood residue required for the greenhouse heating. The decision variables are constrained by heat demand, technology, resource availability, moisture content and emission limitations.

4.2.2 Objective function

The objective of this LP model is to minimize the annual total cost of a biomass boiler system. The objective function consists of the capital cost of all physical equipment, labour and operating and maintenance (O&M) costs, the total fuel cost and the emission fee. The capital cost and O&M cost are related to the boiler size which depends on the greenhouse size and its location.

For an existing 2 ha flower greenhouse located in the LFV, a 3.2 MW biomass boiler is used to satisfy the heat demand. The capital cost of such boiler is approximately C$487,500. A full time employee is required to maintain the system. The total labour and O&M cost is roughly C$51,200/y. For a 7.5 ha vegetable greenhouse, the designed boiler size is estimated to be 11.8 MW using the ASAE Standard EP406.3 (ASAE 2003). The labour and O&M costs are around C$148,000/y and a capital cost of C$2,850,000. The cost for an electrostatic precipitator (ESP) for the emission control is about C$435,000 (Piejko 2007). The objective function is formulated to determine the annual total cost. The capital cost is part of the annual total cost and is amortized for 25 installments (assumed lifespan of 25 years) with 8% interest rate (Table 4.1).

Table 4.1. Annual total fixed costs

	2 ha Flower Greenhouse	7.5 ha Vegetable Greenhouse
Amortized capital cost – Boiler	C$ 45,668.00/y	C$266,985.00/y
Amortized capital cost – ESP	C$40,750.00/y	C$40,750.00/y
Labour and O&M cost	C$51,200.00/y	C$148,000.00/y
Annual air permit or approval fee	C$200.00/y	C$200.00/y
Annual total fixed costs (TFC)	C$137,818.00/y	C$455,935.00/y

The annual capital and O&M costs are fixed and related to the size of boiler and greenhouse. Variable costs are the main components that minimize the objective function. Two types of variables costs are considered: feedstock cost and emission fee. The average wood pellets and wood residue prices are C$105/t and C$25/t, respectively. Metro Vancouver is currently (as in 2008) proposing a new Air Quality Management Bylaw. With the approval of the proposed amendments, any facility that operates a boiler or heater fuelled with natural gas or biomass is required to obtain an air permit or approval (Metro Vancouver 2008b). The new bylaw will apply an emission fee (C$ per tonne of air contaminant emitted) for various air pollutants such as particulate matter (PM), nitrogen oxides (NO_X) and carbon monoxide (CO). The amount of emissions to the air depends primarily on the type of materials combusted and the emission control system used for the boiler. For instance, wood residue combustion tends to generate more PM than that of wood pellets (PM_{10} factor for wood residues and wood pellets are 0.1376 kg/GJ and 0.1161 kg/GJ, respectively based on old but one of the few available data base (EPA 2003)). Thus, the emission fees are related to the amount of wood biomass combusted (i.e. decision variables).

4.2.3 Heat demand constraint

The indoor temperature for flower greenhouses is lower than that for vegetable greenhouses. The heat and CO_2 requirements depend on the type of flowers. On average, the indoor temperatures for a 2 ha orchid greenhouse and a 7.5 ha vegetable greenhouse are 11^{o}C and 21^{o}C, respectively. A monthly heat demand equation (Equation 4.1) was developed based on the ASAE Standard EP406.3 (ASAE 2003) for calculating the annual heat demand using the average hourly temperatures for Vancouver and the average indoor temperature.

$$q_m = 3600AU\sum_{j=1}^{12} N_j \sum_{i=1}^{24}(T_i - T_{oi}) \qquad (4.1)$$

where q_m is the monthly heat demand; A is covered area (m^2); U is overall heat transfer coefficient (W/(m·^{o}C)); N is the number of days in month j; T_i is the average indoor temperature and T_{oi} is the average hourly outdoor temperature over the month . The annual heat demand for the flower and vegetable greenhouses are estimated to be 6,250 GJ/ha and 24,000 GJ/ha, accordingly. The boiler system must combust enough biomass materials to satisfy these demands (Figure 4.1).

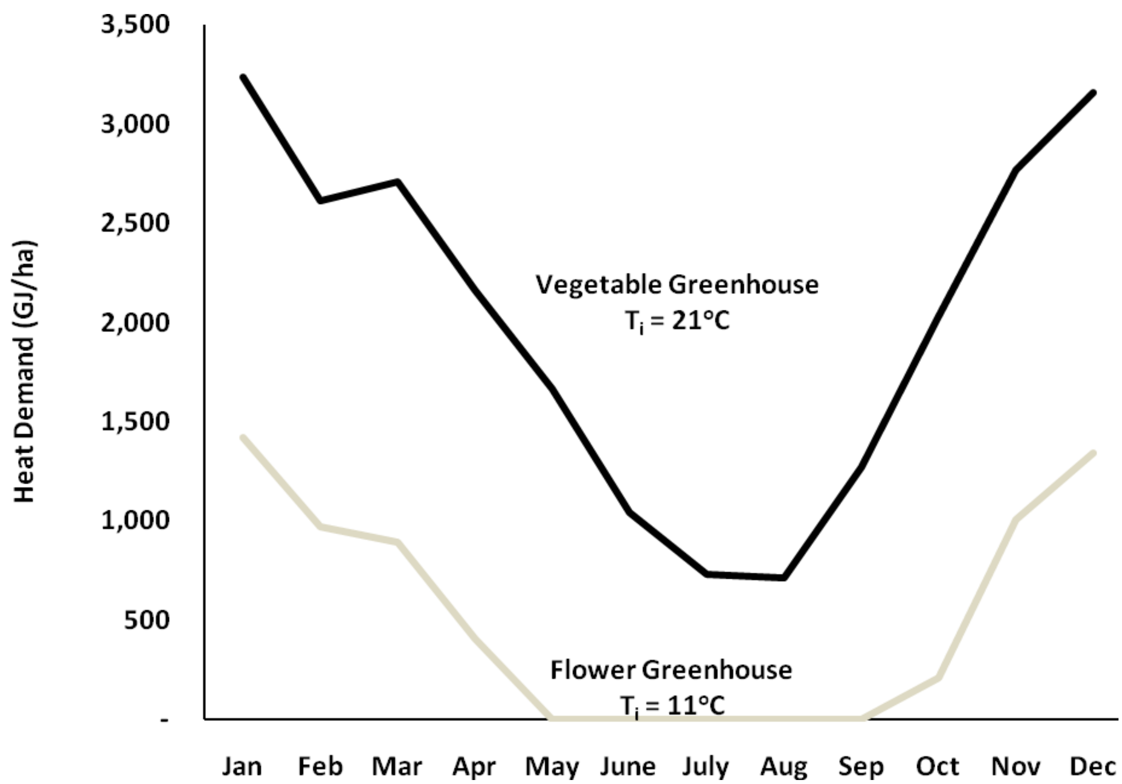

Figure 4.1. Estimated annual heat demadn (GJ/ha) for a vegetable greenhouse and a flower greenhouse in the LFV of BC

4.2.4 Technology constraint

According to the ASAE Standard EP406.3 (ASAE 2003), the boiler size can be determined with the 99% winter design dry bulb temperature (-4.5^{o}C for Vancouver area). It ensures the boiler has sufficient capacity in case of extreme weather. For example, a 2 ha flower greenhouse in LFV uses a 3.2 MW boiler; the capacity is above the designed boiler size (2MW) and the designed heat demand (0.38 MW). A 7.5 ha vegetable greenhouse must install a 11.8 MW boiler which is above the annual heat demand of 5.2 MW. The technology constraint prevents the boiler being overloaded by limiting the output energy from the boiler to be less than or equal to the boiler's maximum capacity or the designed boiler size.

4.2.5 Resource availability

Although wood biomass is a sustainable energy, the available resources are scanted. The total amount of wood pellets produced in BC during 2008 is approximately 980,000 t and is marketed as animal bedding, fuel for energy generation (power and heat, primarily in export market), and for greenhouse heating application (Peksa-Blanchard et al 2007). BC, as the largest lumber-producing province in Canada, produced around 6.5 millions dry t of wood residues in 2004; with a surplus of 1.8 millions dry t available (Bradley 2006). However, the maximum economic distance to transport wood residues is 200 km radius of a power plant (Natural Resources Canada 2006) if the residue is used for direct energy conversion. A rough estimation of the residue within economic range in the LFV region is 204,905 t, which is considered in the LP model (Natural Resources Canada 2006). Assuming all greenhouses in BC (with total area of 511 ha (Statistic Canada 2007)) were to use only wood pellets and wood residues as heating fuels, the resource limitations is estimated using the following equation.

$$\text{Resource Limitation } (\text{RA}_i) = \frac{\text{Total resource available (t)}}{\text{Total greenhouse area (ha)}} \times \text{Studied greenhouse area (ha)} \tag{4.2}$$

4.2.6 Moisture content constraint

Houck et al. (1998) identified that PM emission is minimal if biomass moisture content is between 15% and 25%. Materials with higher moisture content will reduce the combustion temperature which leads to incomplete combustion, and consequently increased emissions. On the other hand, low moisture content material will vaporize volatile organic compounds (VOC) which will escape through the boiler stack. Therefore, wood pellets and wood residue are mixed prior to combustion. The overall moisture content of the mixture should fall between 15% and 25%. Moisture content is the percentage of water contained in the material based on the wet weight of the material (Equation 4.3)

$$MC\% = \frac{M_W - M_D}{M_W} \times 100\% \tag{4.3}$$

where M_W is the wet weight and M_D is the oven-dried weight.

When different moisture content materials are combined, the moisture content of the mixture will change. To determine the moisture content of the mixed biomass, Trautmann and Richard (2007) suggested an equation to estimate the new moisture content

$$MC_x = \frac{\sum_i^n (X_i MC_i)}{\sum_i^n X_i} \tag{4.4}$$

where MC_x is the moisture content of fuel mix, X_i is the amount of fuel *i* and MC_i is the average moisture content of fuel *i*.

The moisture content of the combined biomass should be within the following range (Equation 4.5) to minimize the PM emission

$$15\% \leq MC_x \leq 25\% \tag{4.5}$$

4.2.7 Emission limit constraint

The proposed amendment of the new Air Quality Bylaw from Metro Vancouver indicates an upper emission limit for PM_{10}, $PM_{2.5}$, NOx and CO (Table 4.2).

Table 4.2. Emission limits of the proposed amendments for natural gas and biomass boilers (Piejko 2007)

Contaminants	Emission limit (EL_j)		Proposed emission fee (CE_{ij})
	Natural gas boiler	Biomass boiler[a]	
PM_{10} (mg/m^3)	5	15	C$300/t
$PM_{2.5}$ (mg/m^3)	10	15	C$300/t
NO_x (mg/m^3)	60	120	C$50/t
CO (ppmv)*	400	400	C$30/t

[a] Regulation for urban area (Metro Vancouver 2008b)
* ppmv = parts per millions volume

The upper emission limits for biomass boiler are formulated as constraints in the model. Based on the amount of wood biomass required for combustion and the associated emission factors provided by IPCC, EPA and Metro Vancouver (EPA 2003, IPCC 2006, Metro Vancouver 2008a), the average emissions for each air contaminant are estimated. The PM emission from Metro Vancouver limits were set assuming that proper operating PM emission control equipment, such as ESP, is installed and used. With ESP, the PM emission factor is significantly reduced from 0.1376 kg/GJ to 0.0172 kg/GJ (EPA 2003). The new regulation will require facilities to perform emission testing at least once a year for boilers or heaters located in rural area, and at least twice a year in urban area (Metro Vancouver 2008b). Each emission test costs approximately C$3,000 to C$5,000.

4.2.8 Mathematical model

The objective function and constraints are formulated as an LP model with the following decision variables and parameters.

Objective Functions:

Min Z = Total material cost + Total emission fee + Total annual fixed cost

$$Min\ Z = \sum_{i}^{n} C_i X_i + \sum_{j}^{m} \sum_{i}^{n} CE_{ij} EF_{ij} X_i H_i E_i + TFC \quad (4.6)$$

where

X_i = Amount of fuel i required to generate heat demand (t/y), i = 1...n (1 = wood pellets; 2 = wood residue)

C_i = Delivered cost of fuel i ($/t)

E_i = Boiler efficiency for fuel i (%)

H_i = Heat value (or calorific value) of fuel i (GJ/t)

MC_i = Average moisture content of fuel i (%)

RA_i = Amount of fuel i available (t)

TOH = Theoretical operation hours, 8,760 h/y

EF_{ij} = Emission factor for combusting fuel i to generate emission substance j (kg per GJ of generated energy), j = 1...m (1 = PM_{10}, 2 = $PM_{2.5}$, 3 = NO_x, 4 = CO)

CE_{ij} = Emission cost of producing emission substance j from fuel i ($/t)

EL_j = Emission limit of emission substance j (mg/m^3 or ppmv)

TFC = Total annual fixed cost, including amortized capital cost and O&M cost ($/y)

TGH = Total greenhouses size in BC (ha)

GH = Size of the studied greenhouse (ha)

HD = Heat demand for the studied greenhouse (GJ/y)

CB = Boiler capacity (existing or designed size) (MW)

FGR = Flue gas output rate (m^3/h)

Constraints:

The output energy from the wood biomass combustion should be greater than or equal to the required heat demand

$$\sum_{i}^{n}(X_i H_i E_i) \geq HD \tag{4.7}$$

The output energy must be less than or equal to the maximum capacity of the boiler.

$$\frac{\sum_{i}^{n}(X_i H_i E_i)}{TOH * 3.6GJ/hr/MW} \leq CB \tag{4.8}$$

where 3.6 GJ/h/MW = conversion factor

The amount of wood biomass used should be less than or equal to the available resources

$$X_i \leq RA_i \text{ for all } i \tag{4.9}$$

Moisture content of the mixture is greater than or equal to 15%

$$\sum_{i}^{n}(X_i MC_i) - (15\% * \sum_{i}^{n} X_i) \geq 0\% \quad (4.10)$$

Moisture content of the mixture is less than or equal to 25%

$$\sum_{i}^{n}(X_i MC_i) - (25\% * \sum_{i}^{n} X_i) \leq 0\% \quad (4.11)$$

Air containment emission must be less than or equal to the limitation.

$$\frac{\sum_{i}^{n}(EF_{ij} X_i H_i E_i)}{TOH * FGR} \leq EL_j \text{ for all } j \quad (4.12)$$

For carbon monoxide (CO) constraint, the equation is multiplied by the conversion factor of 24.45 L/mol (which 1 mole of CO = 28.01 g of CO) (Kamrin 1997) for converting the unit to ppmv.

A non-negative constraint is added to avoid resulting negative solutions. In Microsoft Excel Solver, this constraint can be replaced by the "non-negative" assumption.

$$X_i \geq 0 \quad (4.13)$$

4.3 Data analysis

A 2 ha flower greenhouse and a 7.5 ha vegetable greenhouse were studied. The flower greenhouse has no CO_2 requirement, and it is assumed that the vegetable greenhouse uses liquid CO_2 to satisfy the demand. The CO_2 demand and the related cost were not included in order to simplify the modeling. The input parameters related to the greenhouses are shown in Table 4.3.

Table 4.3. Greenhouse information summary

	Flower Greenhouse	Vegetable Greenhouse
Area (GH)	2.0 ha	7.5 ha
Average indoor temperature	11.0 ^{o}C	21.0 ^{o}C
Annual Heat Demand (HD)	11,966.62 GJ/y	164,146.57 GJ/y
Boiler capacity (CB)	3.2 MW	11.8 MW
Boiler efficiency (E_i)	77.0%	77.0%
Resource availability (RA_i):		
Wood pellets	3,835.62 t	14,383.56 t
Wood residue	801.98 t	3,007.41 t

Two decision variables were considered in the model (wood pellets and wood residues), in which wood residue consists of pure shavings and wood chips (Red Cedar and Douglas-fir) from sawmills. Other biomass materials, such as hog fuel, can be included in the LP model. However, wood pellets and wood residue are more commonly used wood biomass in greenhouses. Wood biomass properties are summarized in Table 4.4.

Table 4.4. Biomass information summary

	Wood Pellets	Wood Residue
Delivered cost (C_i)	C$105.00/t	C$25.00/t
Heat value (H_i)	17.94 GJ/t	10.60 GJ/t
Moisture content (MC_i)	4.20%	60.00%
Flue gas output (FGR)	8,495 m^3/h	5,947 m^3/h
Total availability	980,000 t	534,000 t
Emission factor (EF_{ij}):		
PM_{10} (with ESP)	0.0172 kg/GJ	0.0172 kg/GJ
$PM_{2.5}$ (with ESP)	0.01505 kg/GJ	0.01505 kg/GJ
NO_X	1.98 kg/t	0.99 kg/t
CO	0.2580 kg/GJ	0.2580 kg/GJ

The Microsoft Excel Solver is used to solve the LP model. The Solver determined an optimal feasible solution which minimized the objective function and satisfied all constraints for each studied greenhouse. Table 4.1 to 4.4 list input parameters for the 2 ha flower greenhouse case and the 7.5 ha vegetable greenhouse case. Results from the sensitivity analysis are also presented in the following section.

4.4 Results and discussion

The LP model was solved with input data for the 2 ha flower greenhouse and the 7.5 ha vegetable greenhouse. A feasible optimal solution was determined for each case (Table 4.5).

Table 4.5. LP solution summary

	2 ha Flower Greenhouse	7.5 ha Vegetable Greenhouse
Wood pellets (t/y)	641.15	10,105.84
Wood residue (t/y)	381.03	3,007.41
Total material cost (C$/y)	76,846.21	1,136,298.63
Total emission fee (C$/y)	1,365.57	19,632.60
Annual Total cost (C$/y)[a]	216,029.78	1,611,866.23
Heat Demand (GJ)	11,966.62	164,146.57

[a] Included annual fixed costs from Table 4.1

The optimum fuel mixture for the 2 ha flower greenhouse is 641 t of wood pellets and 381 t of wood residues, while the optimum mixture for a 7.5 ha vegetable greenhouse is 10,106 t of wood pellets and 3,007 t of wood residues.

The minimum annual total cost of combusting wood biomass to satisfy the heat demand of a 2 ha and a 7.5 ha greenhouse are C$216,029.78 and C$1,611,866.23, respectively. The amortized capital cost accounts for 40% and 19% of the annual total cost of the 2 ha greenhouse and the 7.5 ha greenhouse, respectively. The optimal material cost for the 2 ha flower greenhouse, $76,846.21 per year, was compared to the material cost from an existing greenhouse which is currently combusting a mix of wood pellets and wood residue to generate heat. On average, the existing greenhouse spent approximately $95,000 for the materials costs with 720 t of wood pellets were used per year. By optimizing the biofuels mix, there is almost 20% reduction on the total material cost. In addition, an ESP must be used to reduce the PM emission efficiently and to reach the new emission limits. Without an ESP, the PM emission would be determined using the PM emission factor without any control equipment associated.

Consequently, no feasible solution was determined as the new PM emission limits could not be satisfied.

The above solutions are optimum only with the given parameters and restrictions. To investigate the impact of changes in parameters on the optimum solution, sensitivity analysis was performed (Beasley 2007, Jensen and Bard 2003). The answer and sensitivity reports generated by Microsoft Excel Solver (Tables 4.6 and 4.7) show the optimality and feasibility ranges. Wood residue is a by-product from most sawmills and therefore are sold at no or low value, but has a transportation cost attached to it. As wood biomass becomes a more popular alternative energy fuel in various industries, there will be an increasing wood residue demand, and consequently an increase in wood residue price is expected. Based on the range of optimality in Table 4.6 and Table 4.7, even if the price of wood residue increases to C$63.08/t (which is an increase of 150% of considered price in this study) or the price of wood pellets decreases to C$43.38/t (which is a decrease of 58% of considered price in this study), the optimum mix of wood residue and wood pellets for greenhouses will remain the same. The range of feasibility (Table 4.6 and Table 4.7) indicates that if the annual heat demand of greenhouses increases by 1 GJ, the annual total cost will increase by C$6.54 and C$7.73 for a 2 ha flower greenhouse and a 7.5 ha vegetable greenhouse, respectively.

Table 4.6. Optimality and feasibility ranges for a 2 ha flower greenhouse

	Original Value	Lower Range	Upper Range	Shadow Price (C$/unit)
<u>Range of Optimality:</u>				
Wood pellets (C$/t)	106.75	43.38	Infinity	
Wood residue (C$/t)	25.63	0.00	63.08	
<u>Range of Feasibility:</u>				
Heat Demand (GJ/y)	11,966.62	0.00	25,187.17	6.54
Wood Pellets Availability (t/y)	3,835.62	641.15	Infinity	0.00
Wood Residue Availability (t/y)	801.97	381.03	Infinity	0.00

Table 4.7. Optimality and feasibility ranges for a 7.5 ha vegetable greenhouse

	Original Value	Lower Range	Upper Range	Shadow Price (C$/unit)
Range of Optimality:				
Wood pellets (C$/t)	106.75	43.38	Infinity	
Wood residue (C$/t)	25.63	0.00	63.08	
Range of Feasibility:				
Heat Demand (GJ/y)	164,146.56	94,451.91	197,645.61	7.73
Wood Pellets Availability (t/y)	14,383.56	10,105.84	Infinity	0.00
Wood Residue Availability (t/y)	3,007.41	2,497.68	5,226.54	-37.45

If the proposed Air Quality Management Bylaw by Metro Vancouver is approved, the emission limitations in Table 4.2 will be applied to boilers; these limitations are unlikely to be increased. Although the results shown that the emission from wood biomass combustion could be below the emission limitations, the results were based on a theoretical calculation with the application of an ESP system. Emission testing must be performed at least twice a year to ensure the air quality from the combustion site. The sensitivity analysis indicates that there is no cost associated with the change of emission limits only with the operation of advance emission control system included in the model to obtain the low level of emissions. The capital costs of these equipments were included in the objective function as part of the annual total cost.

The above sensitivity analysis results can provide useful information for the management in terms of the change in material prices and constraints. However, the optimality and feasibility ranges provide valid solutions only for one parametric change at a time. Any alternative optimal fuel mix should be re-determined by the Solver when two or more changes are applied (Jensen and Bard 2003).

4.5 Conclusion

An LP model was formulated to determine the optimum mix of biomass fuel for a greenhouse heating application. The model's objective was to minimize the annual total cost including materials cost, emission fee, amortized capital cost, and O&M cost. The model was constrained with heat demand, technology requirement, resources availability, and emission limits. It was applied to a 2 ha flower greenhouse and a 7.5 ha vegetable greenhouse. A feasible optimal solution was determined in each case. To provide heat demand for a 2 ha flower greenhouse with the minimum annual total cost, a mix of 641 t of wood pellets and 381 t of wood residues was estimated to be the optimum. Similarly for a 7.5 ha vegetable greenhouse, a mix of 10,106 t of wood pellets and 3,007 t of wood residues was estimated to be the optimum.

In January 2008, Metro Vancouver proposed an amendment to the Air Quality Management Bylaw. The amended bylaw if approved requires all facilities with boilers or heaters using natural gas or biomass to obtain an air emission permit. To meet the PM emission limits, an ESP system must be installed if biomass is used as a fuel. Without ESP, no feasible solution can be found. The sensitivity analysis indicate that the optimal fuel mix for both greenhouses will remain the same even when the wood pellets price is reduced to C$43.48/t (58% decrease) or the wood residue price is increased to C$63.08/t (150% increase).

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Chapter 5. Conclusion and Future Research

5.1 Conclusion

The greenhouse industry is one of the important sectors of the Canadian agri-food industry, generating C$2.35 billions of total sales in 2006 (Statistic Canada 2007). Although the total sales of greenhouses have increased by 187% since 1995, the industry is facing increased competition from foreign producers (Statistic Canada 2006). The primary fuel used in the greenhouses is natural gas, which accounts for approximately 28% of the total operating expenses in the BC greenhouse industry (BCMAFF 2003). Natural gas is used to generate heat and carbon dioxide (CO_2) to enhance the crop productivity. Natural gas combustion is considered to be an easy and clean process to provide heat for greenhouses. The flue gas from natural gas combustion is considered by the greenhouse industry to be clean enough to inject into the greenhouse to increase the CO_2 level. However, natural gas combustion produces fossilized carbon and other greenhouse gases contributing to the global warming effect. Fluctuating gas prices coupled with environmental concerns, has become the main driving force for the greenhouse industry to consider alternative energy sources.

Since 2001, there have been an increasing number of greenhouses converting to wood biomass heating system to reduce the usage of natural gas (Melin 2006). Wood biomass is considered to be a "carbon neutral" material as the carbon released through combustion is the same amount of carbon absorbed during the biomass production. Nevertheless, the industry cannot foresee biomass as a dependable and predictable fuel due to the uncertainty in resource availability, fuel price and quality, and air quality concerns.

This research was designed to evaluate the economic feasibility of using wood biomass for greenhouse heating applications, investigate the sensitivity on the feasibility to changes in market prices and other parameters, assess the environmental benefits of using wood biomass, and determine the optimal fuel mix. Three studies were completed to achieve these objectives.

The economic analysis was done using the Net Present Value methodology. Four scenarios were investigated to define the feasibility of using wood biomass to generate a portion of the heat demand (40%) for the average sized (7.5 ha) greenhouse. In this study, the variables considered included greenhouse size and structure, boiler efficiency, fuel types, and source of CO_2 for crop fertilization. The NPV of the four scenarios were calculated using the engineering economics method and the Canadian capital cost allowance guideline with the assumed lifespan of 25 years. At the desired discount rate, four scenarios returned a positive NPV indicating the installation of a wood pellets or a wood residue boiler for providing portion of heat demand is more economical than using a natural gas boiler to provide all heat and CO_2 demands. Furthermore, using a wood biomass boiler could significantly reduce the emission of greenhouse gases. However, wood biomass combustion may generate higher emission of particulate matters (PM) than that of natural gas combustion; an advanced emission control system is needed to eliminate this issue.

The second study of this research, an extension of the techno-economic analysis, focused on the impacts of technical and market changes to the economic feasibility of wood biomass to produce heat for an average sized vegetable greenhouse. In this study, the effects of fuel price, energy contribution, and greenhouse size changes on the NPV of the four scenarios of wood biomass boiler systems were evaluated. Cost saving from using a wood biomass boiler is one of the main driving forces to obtain the economic benefits. Therefore, increasing natural gas prices or decreasing wood biomass prices would increase the attractiveness of wood biomass combustion. By increasing the energy contribution from a wood pellets or a wood residue boiler, higher NPVs were achieved as greater savings were associated with reduced natural gas usage. However, the results did not show economic feasibility for a wood biomass boiler to provide a small portion of heat for a typical greenhouse. Moreover, wood biomass boilers were shown to be more suitable for an average to a large sized greenhouse.

The third study of this research focused on the feasibility of combusting wood biomass with the constraints of resource availability and environmental limitations. In this study, a linear programming (LP) model was developed to determine the optimal biomass fuel mix (wood pellets and wood residue) for the generation of heat to a greenhouse. Two cases were studied: a 2 ha flower greenhouse and a 7.5 ha vegetable greenhouse. The objective function of the LP model was to minimize the annual total cost of wood pellets and wood residue combustion, while constraints were added to the model to satisfy the heat demand, resources availability and emission limits. In order to satisfy the emission limits from Metro Vancouver's amendment, an ESP system was considered to be used. The optimum cost of biomass for the case of 2 ha flower greenhouse was compared to that of an existing greenhouse. The results showed a significant reduction in the total fuel costs per year. A sensitivity analysis also indicated that these optimal solutions would not be affected with changes in material costs.

5.2 Limitations

This research focuses on the use of biomass as a renewable energy source for greenhouses and in order to complete the studies several assumptions were made. The data were collected by surveying greenhouses which currently use wood pellets or wood residue to provide partial or their entire heat demand and present average estimates for the studied greenhouses only. Financial parameters such as capital cost for a different size boiler considered in the study were based on estimates from experts and engineering formula. More accurate data on monthly heat and CO_2 demand by crop types, materials price and demand, and actual boiler efficiency should be obtained in order to increase the evaluation accuracy.

The techno-economic analysis and the optimization analysis included the environmental benefits of using wood biomass for the greenhouse heating application. However, the results were based on the theoretical amount of biofuels, the theoretical boiler operation hours, and the emission factors of wood fuel from IPCC, EPA and Metro Vancouver. Data from actual emission testing should be included to obtain accurate emission information. In addition, the environmental benefits such as carbon credits or governmental incentives were not considered in the analyses, while the consideration could increase the attractiveness of wood biomass projects.

Carbon dioxide demand is another important factor that was eliminated in the study. Most of the greenhouses that combust wood biomass for heat are still combusting natural gas to provide CO_2 for the greenhouses. The actual amount of CO_2 requirement for a special greenhouse is not available as it is difficult to extract such information from the natural gas demand for heat. Therefore, the case studies considered the use of natural gas boiler or liquified CO_2 to satisfy the demand. However, the cost benefit of such CO_2 sources was not considered in any study of this research.

5.3 Future research

This research can be extended in different ways. For instance, the studies purely considered the economical benefits of combusting wood biomass with a brief indication of the environmental impacts from wood biomass. Further investigation such as Life Cycle Analysis (LCA) of wood biomass could be developed to evaluate the environmental impacts of preparing, producing, and transporting wood biomass. An LCA study defines the environmental and health impacts of a product or a process from cradle to gate. The LCA results for wood biomass and natural gas can also be compared to identify the environmental benefits of one energy source to another.

It was assumed that all greenhouses had an existing natural gas boiler installed. Therefore, the capital cost of a natural gas boiler was excluded and the scenarios were designed to use the existing natural gas boiler for 60% of heat and CO_2 demand, with a new installation of wood biomass boiler to generate the rest of heat demand. Other comparisons such as the installation of a new boiler (wood biomass and natural gas) for a new greenhouse can be completed to identify the long-term benefits of using wood biomass. Since some greenhouse owners cannot foresee the current benefits of converting into wood biomass boiler, an economic study can be completed to determine the economic life of the existing natural gas boiler. The economic life defines the lifetime of an asset that will minimize the average annual cost. However, all relevant costs associated with the wood biomass boiler and natural gas boiler must be considered in order to perform an accurate evaluation.

Finally, the LP model can be extended into a dynamic model which includes a monthly demand of the biomass fuel mix. Based on the past experience, the wood residue production from sawmills decreases during winter season. Consequently, it will affect the resource availability in the model. Including monthly inventory and demand variables in the LP model can help a greenhouse operator forecasts the supply and manages the fuels inventory. This factor was not included in this research because only the annual wood pellets and wood residue production were collected. More accurate information such as monthly wood residues production from a specific sawmill should be collected to develop a dynamic LP model.

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