

**MULTI CRITERIA EVALUATION OF WOOD PELLET  
UTILIZATION IN DISTRICT HEATING SYSTEMS**

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF  
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES  
(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA  
(Vancouver)

February 2011

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## Abstract

The hypothesis that this thesis investigates is that “the wood pellet is a competitive primary energy source option for generating district heat in Vancouver, BC”. The competitiveness of the wood pellet as an energy source is evaluated by investigating a major district heating project in Vancouver, BC in which the wood pellet option was compared with natural gas, sewer heat, and geothermal heat. It is observed that in addition to technical and economic factors, environmental and social acceptability criteria play an important role in the selection of the energy source for district heating systems. These include stakeholders’ concerns regarding global warming impacts associated with production and transportation of the wood pellets, as well as particulate matter emissions from wood pellet combustion at the facility. In order to investigate the hypothesis, detailed study of: (a) particle emissions formation and levels, (b) techno-economic performance, and (c) upstream and life-cycle environmental impacts when using wood pellets at the district heating centre, has been carried out. This thesis accepts the hypothesis in that:

1. Particulate emission levels from wood pellet combustion when an electrostatic precipitator flue gas cleaning system is used is below the  $18 \text{ mg/m}^3$  (20°C, 101.3 kPa, 8% O<sub>2</sub>) regulatory limits in Vancouver, BC,
2. The cost of heat generation (CAD/MWh<sub>th</sub>) from the wood pellet option (19.08~23.66) is comparable to that of the natural gas option (17.38) and well below those of the heat pump options (26.34~30.71),
3. Based on the upstream environmental impacts of the energy options, a single energy option, which outperforms others when all the impact categories at the same time are considered, cannot be identified. However, it was shown that the impact of upstream production and transportation activities for the wood pellet option does not offset the global warming mitigation advantage of this option. The greenhouse gas equivalent of upstream emissions from the wood pellet option is in the same order of magnitude as the renewable heat pump options, and has remarkably lower (less than 200 kg<sub>eq</sub> of GHG emissions per MWh of produced district heat) than that of the natural gas option.

## **Preface**

The research reported in this thesis which consists of thesis hypothesis development, critical review of literature, consultation with industry experts, planning the study, gathering data, evaluating the data, developing and running decision support models, and analyzing the results, were conducted by the author, Saeed Ghafghazi. The topic of dissertation was proposed by my academic advisers Dr. Shahab Sokhansanj and Dr. Taraneh Sowlati. The City of Vancouver Engineers were extensively consulted. The thesis includes four manuscripts:

- A version of Chapter 3 has been published. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Melin, S. (2010), A multi criteria approach to evaluate district heating system options. *Applied Energy*, 87 (4): 1134-1140.
- A version of Chapter 4 has been submitted for publication. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, T., Melin, S., Particulate matter emissions from combustion of wood in district heating applications.
- A version of Chapter 5 has been published. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Melin, S. (2009), Techno-economic analysis of renewable energy source options for a district heating project. *International Journal of Energy Research*, DOI: 10.1002/er.1637.
- A version of Chapter 6 has been submitted for publication. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, T., Melin, S., Life cycle assessment of base-load heat sources for district heating system options.

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## **Acknowledgements**

I would like to thank my supervisors, Dr. Shahab Sokhansanj and Dr. Taraneh Sowlati, for their time, support, and helpful comments during the work. I would also like to thank other members of my supervisory committee, Dr. Tony Bi, Dr. John Nelson, and Mr. Staffan Melin, for their access and guidance.

I would like to acknowledge the contribution of Mr. Chris Baber, project manager of the Southeast False Creek energy neighborhood, and Mr. John Chin of the FVB Energy Inc. in providing me the data and information on the Southeast False Creek energy neighborhood.

I appreciate the time and help of my examination committee, Dr. Andrew Pollard, Dr. Eric Hall, Dr. Peter Marshall, and Dr. Andrew Riseman.

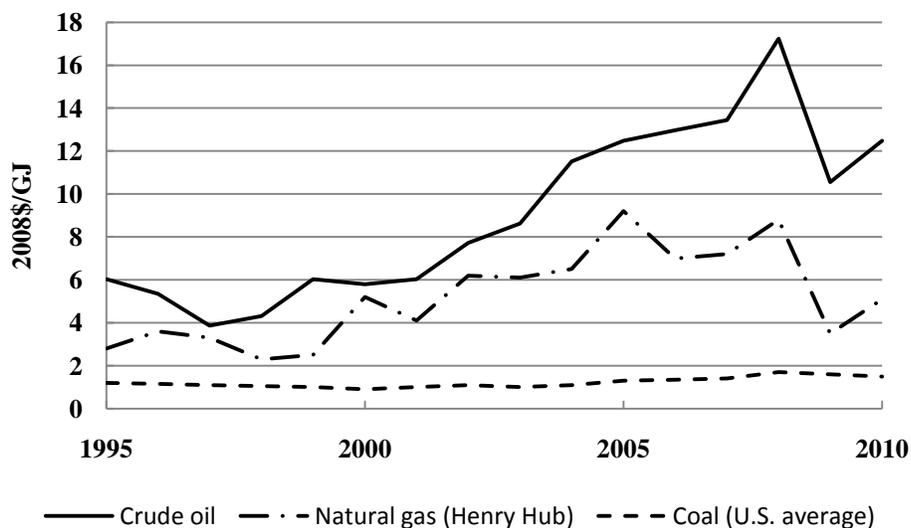
## **Dedication**

To my parents, Shahin and Ali, and my lovely wife, Sara; for their unceasing love and support.

# Chapter 1. Introduction

## 1.1. Background

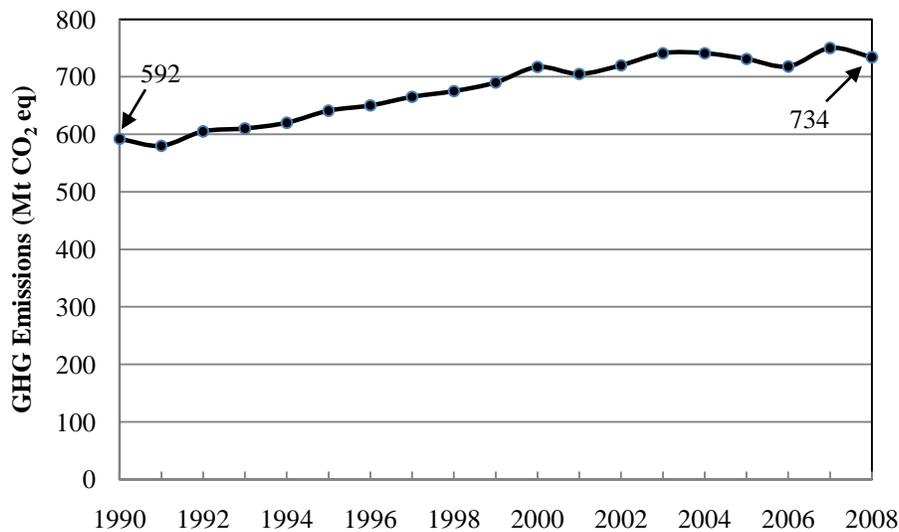
Canada is the seventh largest primary energy consumer in the world (Energy Information Administration, 2008). Fossil fuel sources (natural gas, petroleum, and coal products) constitute more than 70% of Canada's secondary energy use (Natural Resources Canada, 2010). The global warming effect, fuel price increase and instability, and primary resources depletion are major concerns associated with utilization of fossil fuels. As Figure 1–1 shows, the price of major fossil fuels such as natural gas and oil has increased rapidly since 1995 and is projected to increase with the same pace in the next two decades (Energy Information Administration, 2010).



**Figure 1–1: Yearly average fossil fuel prices**  
Adopted from: (Energy Information Administration, 2010)

Although by commitment to the 1997 Kyoto protocol, Canada should reduce its GHG emissions to 240 Mt by 2012 (Islam et al., 2004), the total GHG emissions

generated in Canada has increased by 24.1% of the 1990 levels (Figure 1–2) (Environment Canada, 2010). More than 80% of Canada’s GHG emissions inventory is due to fossil fuels production or consumption (Environment Canada, 2010).



**Figure 1–2: Canada's GHG emissions trend 1990-2008**  
 Adopted from: (Environment Canada, 2010)

Canada requires supplementary policy measures to promote incentives for utilizing energy efficient systems and renewable energies in order to meet the GHG emission reduction goals by the Kyoto protocol (Hofman and Li, 2009). These policy measures at federal and provincial government levels should target various sectors with high GHG emission contributions (Demerse and Bramley, 2008). As Table 1-1 shows, space and water heating in residential and commercial/ institutional buildings is one of the major sources of GHG emissions and energy consumption in Canada.

**Table 1-1: Canada's secondary energy use and GHG emissions by sector in 2007**  
 Adopted from: (Natural Resources Canada, 2009)

|                                   | Total energy use<br>(PJ) | Total growth<br>1990-2007 | Total GHG emission*<br>(Mt CO <sub>2</sub> eq) | Total growth<br>1990-2007 |
|-----------------------------------|--------------------------|---------------------------|--|---------------------------|
| <b>Residential and commercial</b> | 2588.8                   | 20.5%                     | 76.3   | 14.2%                     |
| Space and water heating           | 1833.1                   | 16.3%                     | 74.9   | 13.1%                     |
| <b>Industrial</b>                 | 3471.6                   | 28.1%                     | 118.5  | 19.6%                     |
| <b>Agricultural</b>               | 215.0                    | 7.9%                      | 13.0   | 10.6%                     |
| <b>Transportation</b>             | 2595.2                   | 38.2%                     | 179.2  | 36.4%                     |

\*Excludes electricity generation

Fossil fuels utilization for space and water heating purposes account for 56% of total energy consumption in residential and commercial/ institutional buildings (Cuddihy et al., 2005). Implementing renewable energy technologies to provide the energy requirement for space and water conditioning in residential and commercial/institutional buildings could reduce Canada's dependency on fossil fuels by about 16% and offset GHG emissions by more than 10% (Natural Resources Canada, 2009).

Renewable energy sources include a variety of forms such as biomass, sunlight, wind, ocean waves, tides, and geothermal heat. These energy sources are called renewable since they are naturally replenished in a short cycle. Renewable energy had been proven to be a viable and economic option for a growing list of consumers and uses (International Energy Agency, 2004). Renewable energies contribute to the three pillars of sustainable development: economy, environment and social well-being (International Energy Agency, 2004).

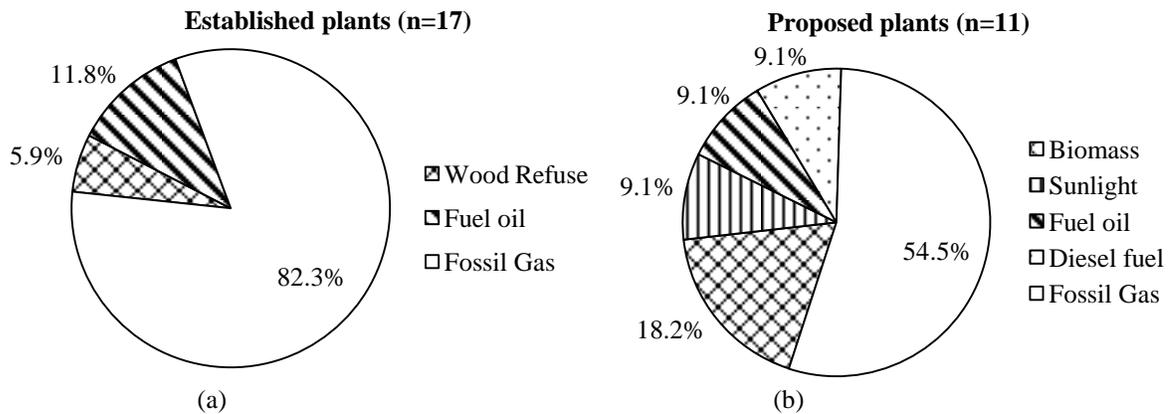
Penetration of renewable energy technologies into the buildings space and water heating sector, especially at small scale consumers level, faces several barriers (Painuly, 2001; Islam et al., 2004; Reddy and Painuly, 2004; Foxon et al., 2005; Cooke et al., 2007):

- High capital cost and therefore longer payback periods associated with renewable energy technologies, which is seen as the most important barrier,
- General unfamiliarity of consumers with the available renewable energy technologies,
- Consumers' negative perception about quality, risk, and usefulness of renewable technologies when compared to the conventional technologies,
- Higher costs and market inefficiencies of renewable energy technologies.

The utilization of renewable energy sources to provide heating requirement of buildings can be measured and better pursued by developing centralized district heating system (Grohnheit and Mortensen, 2003). A district heating system is a centralized heat producing system that produces and distributes hot water or steam for space heating and/or domestic hot water use purposes for several buildings within a community. Opportunities for competition between fuels and technologies are remarkably higher in

district heating systems due to higher initial investment possibility and economies of scale associated with these systems (Grohnheit and Mortensen, 2003). Also, higher overall energy efficiency, lower produced energy cost, and possibility of utilizing environmental impact control systems are among competitive advantages of district heating systems compared to heating options available for individual buildings in areas of high heat load density (Gochenour, 2001).

The district energy system industry in Canada was introduced in the early 1880s and is still a growing industry throughout the country (Gilmour and Warren, 2008). Traditionally, fossil fuel sources were the major primary energy sources in Canadian district heating centres (Gilmour, 2007). Recent district heating projects, however, tend to utilize more renewable energy sources as primary heat source option. Figure 1–3 which is prepared based on an industry survey, shows the share of energy sources in established and new plants in Canada in 2007 (Gilmour, 2007).



**Figure 1–3: Share of fuel type in the Canadian established and proposed district energy plants (year 2007)- Source: (Gilmour, 2007)**

The establishment of district heating systems usually involves government support at local, regional, and national levels, because “market forces may drive solutions that may be shorter term than is optimum for society and discriminate against high capital technologies such as district heating” (International Energy Agency, 1999). Also, from the financial point of view, most district heating projects throughout the world rely to some extent on government subsidies, since these projects require high capital

investments with “patient” investors who can embrace longer payback periods (Gochenour, 2001). Table 1-2 shows various government and non-government stakeholder groups that can generally be recognized in the development of district heating projects in Canada.

**Table 1-2: Typical stakeholder groups involved in the development of district energy centres in Canada - Source: (Gilmour and Warren, 2007)**

| <b>Areas of interest</b>                                   | <b>Stakeholders</b>   |
|--|---|
| Federal Government   | Natural Resources Canada<br>Public Works and Government Services<br>Department of National Defense<br>Finance Department<br>Environment Canada<br>Crown Corporations, ex Canada Mortgage Housing Corporation, Canada Lands Corporation, Canada post |
| Provincial Government                                      | Ministry of Energy<br>Ministry of Environment and/or Parks<br>Ministry of Infrastructure<br>Ministry of Planning and Municipal Affairs<br>Provincial crown agencies and Aboriginal Business Canada, such as Energy Boards                           |
| Municipal Government and Aboriginal Business Canada (ABCs) | Planning<br>Engineering and Works<br>Infrastructure<br>Permits and licenses<br>Building standards/ Real Estate<br>Local Utility   |
| Utility companies (private and public)                     | Electricity, gas and alternative energy companies   |
| Private companies  | Professionals (designers, architects engineers)<br>Equipment suppliers<br>Building owners, managers and developers<br>Financial institutions, pension funds and investors<br>Independent power producers  |
| Independent groups   | Federation of Canadian Municipalities<br>Canadian District Energy Association<br>Environmental groups<br>School boards  |
| Community and Users  | Benefactors of district energy system – Building occupants, residents, etc.   |

The involvement of several government and non-government stakeholder groups in the development of district heating projects increases the complexity of decision making especially regarding the key issues to be considered such as the choice of facility heat source (Pembina Institute, 2010). Stakeholders’ concerns and preferences about the performance of a heat source or technology considered for the district heating system can

vary and sometimes can be in conflict. The decision makers are required to approach the question of “suitability” of “energy source option” for the district heating centre from a multi-faceted angle. The aim of considering various factors is to address various stakeholder groups’ concerns and preferences.

## 1.2. District heating and renewable energy in British Columbia

Utilizing renewable energy sources in district heating systems in British Columbia has received increased attention in recent years. Table 1-3 lists a number of district heating centres in BC. As it can be seen, natural gas has been the main source of energy in the already established district heating plants, while in new district heating systems, the base-load energy requirement of the district heating centres is mainly provided by renewable sources and natural gas is used to meet peaking and backup demand.

**Table 1-3: Examples of district energy centres in British Columbia**

| <b>District heating centre</b>           | <b>Location</b> | <b>Heat source</b>                                     | <b>Commission year</b> |
|--|-----------------|--|------------------------|
| University of British Columbia           | Vancouver       | Natural gas  | 1925                   |
| Simon Fraser University                  | Burnaby         | Natural gas  | 1966                   |
| Okanagan College                         | Kelowna         | Natural gas, over 60% from sewage heat recovery, solar | 2004                   |
| Lonsdale Energy Corp.                    | North Vancouver | Natural gas  | 2004                   |
| Revelstoke Community Energy Corp.        | Revelstoke      | Wood residue   | 2005                   |
| University of British Columbia- Okanagan | Kelowna         | Natural gas, open loop geo-exchange, solar             | 2007                   |
| SEFC Neighbourhood Energy Centre         | Vancouver       | Sewer heat, natural gas                                | 2009                   |
| Dockside Green                           | Victoria        | Wood residue, natural gas                              | 2009                   |
| Whistler Athlete’s Village               | Whistler        | Sewer heat/ natural gas                                | 2009                   |
| University of Northern British Columbia  | Prince George   | Natural gas, biomass gasification                      | 2010                   |

BC’s municipalities have access to a wide range of energy sources. Natural gas is one of the most popular sources of energy all around BC. Its availability is deemed secure because of the well developed network and infrastructure available in the province. Moreover, generating the required district heat from locally available low grade heat sources such as sewer, ground, and process heat, using heat pumps has been practiced in

several communities in BC. Also, most jurisdictions in BC have access to various forms of wood biomass sources, which can be used for energy generation. Moderate investment requirements for wood-based heat producing technologies and low fuel cost, in addition to the GHG neutrality of biomass combustion activity, are the strong points of biomass utilization, which make it a favorable renewable option for energy production purposes (Doukas et al., 2006; Papadopoulos and Karagiannidis, 2008).

BC is rich in biomass and can play a leading role in Canadian and global bioeconomies. British Columbia's forests cover 60 million hectares of the 95 million hectare area of the province (Ralevic and Layzell, 2006). In BC, the inventory of mill residue production was 6.5 million BDt<sup>1</sup> in 2006. The majority of mill residues is used for energy production purposes or as raw material for other sectors such as pellet plants; yet the surplus of mill residues in the province was 1.8 million BDt, which accounted for 67% of Canada's mill residue surplus, in 2006. Upon the start up of a major biomass cogeneration plant and pellet producing plants in 2006, this surplus was reduced to 1.3 million BDt (Bradely, 2006). There is also an estimated annual surplus of 400,000 BDt pulp chips in the province (Bradely, 2006).

Among the various forms of wood biomass, wood pellets represent a special case in British Columbia. Wood pellet production has increased exponentially in the past decade in BC. In 2008, wood pellet production in Canada exceeded 1.5 million tonnes (Swaan and Melin, 2008). About 1 million tonnes of wood pellets produced in BC were exported to Europe for residential or district heat generation purposes in 2006 (Swaan and Melin, 2008). In fact, the demand for wood pellets for heat generation purposes has increased in some European countries (e.g. Sweden) such that they depend to a certain degree on imports from biomass rich countries such as Canada (Mahapatra et al., 2007). An abundance of raw material and the wide dissemination of biomass-based district heating systems in Sweden have been the leading factors that have fostered the emergence and growth of the Swedish pellet market (Mahapatra et al., 2007). In BC, however, the

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<sup>1</sup> Bone-dry ton (BDt) is a unit used in the forest products industry to measure bulk products such as wood chips or sawdust. One bone-dry tonne is a volume of bulk material (wood chips, etc) that would weigh 2000 pounds (0.9072 metric ton) if all the moisture content were removed.

availability of wood pellet fuels has not been accompanied by a growth in wood pellet demand for energy production purposes in the domestic market. In particular, the recently developed district heating systems in urban areas such as Vancouver have relied on fossil fuels and other renewable energy sources; whereas, wood biomass in general and wood pellets in particular have not been successfully recognized and implemented as a primary energy source.

### **1.3. Thesis hypothesis and objectives**

The hypothesis that this thesis investigates is: “the wood pellet is a competitive primary energy source option for generating district heat in Vancouver, BC”.

In order to address the thesis hypothesis, the barriers in selecting wood pellets as an energy source in district heating systems are studied first by investigating the decision making process of selecting the energy source option for a major district heating project in Vancouver, BC. The objectives sought in the study of the district heating project are to:

1. Identify and understand the major issues considered by various stakeholder groups for using wood pellets in district heating in Vancouver, BC.
2. Investigate how the stakeholders’ perceptions about the energy source options for the district heating system affect the outcome of the decision making process.

Next, to be able to accept or reject the hypothesis, the major issues considered by stakeholders in selecting the wood pellet as a heat source option in district heating systems in Vancouver are assessed in detail through the following objectives:

3. Investigate the significant factors which affect the particulate emission level in the wood biomass combustion flue gas, and determine the particle emission level in the flue gas of district heating systems that utilize wood pellets as fuel.
4. Determine the techno-economic performance of the wood pellet option and compare it with those of other fossil and renewable options in the district heating system, and

5. Investigate the life-cycle environmental impacts of producing district heat with the wood pellet option and compare it with those of other fossil and renewable options.

#### **1.4. Case study**

The City of Vancouver was carrying out a major renewable-based district heating project in 2006, which is selected as the case study in this research. The selected case study represents some issues that are of interest:

- 1) Wood pellets were one of the heat source options that were seriously considered by the district heating developer at the feasibility study phase.
- 2) The decision making process for heat source option selection included various stakeholder groups that are usually present in such projects.
- 3) The main energy source options available for district heating systems in Vancouver were considered.

The considered case is a newly developed district heating system (commenced in Nov. 2009) which provides hot water to a 234,400  $m^2$  floor area in the Southeast False Creek community in the city of Vancouver, British Columbia (BC).<sup>2</sup> The supplied hot water (at 65 °C discharge and 45 °C return) would be used for space heating and the domestic hot water requirements in the buildings. The development area included a mix of building types. The sustainability measures set for this community by the City of Vancouver required all the buildings developed in this community to be connected to a district heating network for space heating and domestic hot water requirements (City of Vancouver, 2009). Since the community was a new development, information about building designs and specifications were not available or poorly developed. Table 1-4 summarizes the estimated total floor area of each building type in the community.

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<sup>2</sup> The data and information used in this study regarding the considered district energy centre were provided by the City of Vancouver (Compass Resource Management Ltd., 2006; FVB Energy Inc., 2006a; FVB Energy Inc., 2006b; Trent Berry, 2006). Since these references are internal reports and not available to the public, the information from these reports, which was used in this study is presented clearly in the text. Also, general information about development of the community and its energy centre is available to the public from City of Vancouver's website at: <http://vancouver.ca/commsvcs/southeast/documents>.

**Table 1-4: Share of building types in the development plan of the Southeast False Creek community**

| Building type                  | Floor area ( $m^2$ ) | Percentage to total |
|--------------------------------|----------------------|---------------------|
| School                         | 3,500                | 1.5%                |
| Office                         | 7,400                | 3.2%                |
| Retail store                   | 13,400               | 5.7%                |
| High-rise residential building | 115,600              | 49.3%               |
| Low-rise residential building  | 94,500               | 40.3%               |

The estimated system capacity to cover the peak load of the community was 10 MW (FVB Energy Inc., 2006a). The heating load of the district heating system has been proposed to be provided by a combination of base-load and peaking/backup systems (FVB Energy Inc., 2006b). It was proposed to have a 2.5 MW base-load system, which would operate at full capacity most of the time. The peaking/backup system would be a 10 MW natural gas boiler to operate at the heat-match mode; that is, when the heat demand exceeds the base-load capacity, the peaking system provides the incremental heat to meet the demand (FVB Energy Inc., 2006a). Having a separate base-load system would allow the exploitation of alternative energy sources to meet the majority of the community's energy demands throughout the year.

The pre-feasibility study phase (FVB Energy Inc., 2006b) considered various energy source options. A natural gas boiler was considered for the peaking/backup system. Natural gas is one of the most popular sources of energy all around BC. The operation of natural gas systems is both easy and reliable because of: 1) well developed combustion systems available in the market, and 2) well developed natural gas networks and infrastructure in the province. These parameters have made natural gas an attractive fuel source for the peaking/backup system. The peaking/backup system requires highly reliable technology to cover the district heating demand in cases when the base-load system is out or not able to meet the peak demand.

The energy sources considered for the base-load system include natural gas, wood pellets, sewer heat, and geothermal heat.

The utilization of natural gas in the base load system facilitates its integration with the peaking and backup natural gas system. Geothermal and sewer heat are renewable energy

sources within the region. Nevertheless, exploitation of these sources requires extensive development in order to be able to utilize these low-grade heat sources. Also heat pumps, which are a major component of these energy producing systems, are electricity intensive equipment. The electricity used to run heat pumps constitute major operating costs for these systems.

## **1.5. Thesis structure**

In addition to the introduction chapter, this thesis includes one literature review chapter, four research chapters, and a chapter on conclusions, limitations, and future work. The rest of the thesis is organized as follows:

Chapter 2 is a literature review on three main subjects used in the research chapters. This chapter starts with the literature review on multi attribute decision making and its application to the energy planning field. Especial attention is paid to the major decision making methods and criteria used for evaluating the suitability of various energy source options in energy production systems. The second part of Chapter 2 reviews the literature on the technical and economic assessment of renewable energy source options for heat and power production systems that have district energy implications. Life-cycle assessment methodology is introduced and studies are reviewed that investigate the life cycle environmental impacts of energy production systems.

Chapter 3 starts with describing the decision making process for the choice of energy source for the district heating centre explained in section 1.4. Then, multi-attribute decision making study on two different scenarios (current situation and an ex-post analysis) is carried out to demonstrate how the ranking of alternatives for stakeholder groups change when issues that concern stakeholder groups are addressed. This chapter also highlights the major conflicting issues for the selection of wood pellets for the district heating application, which shows the pathway for the research chapters to follow.

In Chapter 4, the issue of particulate emissions from wood biomass combustion in district heating systems is studied. Specifically, the effects of three main factors on formation and levels of particulate matter emissions from wood fuel combustion are

investigated: 1) wood fuel property, 2) combustion condition, 3) use of flue gas cleaning equipment. Also, based on direct measurement studies, the levels of particulate matter emissions in the flue gas of wood combustion are compared those limits specified in the air quality bylaw 1087 (Metro Vancouver, 2008) for wood-fired hot water boilers in Vancouver, BC.

Chapter 5 considers a techno-economic study of major technologies that could be used in order to utilize wood pellets in district heating systems. In this chapter, the wood pellet technologies are compared with other major technologies, namely natural gas boiler and heat pump options. The incremental economic performance of various options is calculated in terms of the cost of produced heat per  $MWh_{th}$  at the facility.

Chapter 6 investigates the life cycle environmental impact of producing heat at the district heating centre with the considered heat producing options. The upstream fuel production activities for all the energy options are considered. The emissions from the facility during the service life of the district heating system are included in the life cycle inventory. Also, major materials used for facility construction and landfill or recycling of the materials after the service life are included.

Finally, in the concluding Chapter, the main findings of the thesis are discussed and recommendations for future research direction are made.

## **Chapter 2. Literature review**

### **2.1. Synopsis**

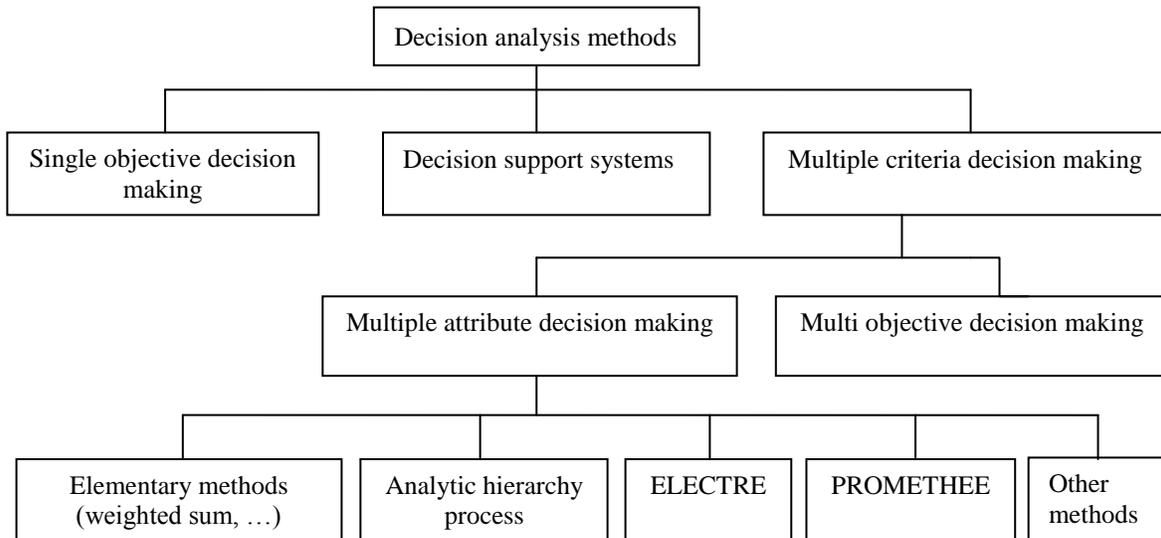
Economic, environmental, technical, political, and social factors and also the trade-offs among them are important in energy related decisions (Crousillat et al., 1993; Hobbs and Meier, 2000; Huang et al, 1995a). Therefore, a multitude of methods have been used in order to aid decision makers to clarify these tradeoffs and reflect upon long term impacts of their decisions (Corner and Kirkwood, 1991).

The purpose of this chapter is to introduce and provide a review on methods and approaches used in the research chapters to follow. First, in Section 2.2 application of the Multi Criteria Decision Making (MCDM) approach in the evaluation of energy systems is discussed, which provides basis for Chapter 3. In Section 2.3, concepts and previous research outcomes for techno-economic assessment of energy source options for heat/power generating plants are reviewed. Section 2.4, which provides basis for Chapter 6, briefly explains the life cycle assessment methodology and reviews studies on life cycle environmental impacts of renewable as well as conventional energy source alternatives utilized in energy producing systems.

### **2.2. Multi attribute decision making in energy systems evaluation**

#### **2.2.1. Multi attribute decision making**

Decision analysis provides a formal methodology for examination of a complex decision making problem, determination and formulation of alternative courses of action, treatment of information, preferences, and evaluation of supposedly the “most preferred” alternative or course of action (Huang et al., 1995a). Figure 2–1 represents a general categorization of decision analysis techniques.



**Figure 2–1: Classification of decision analysis methods - adopted from: (Zhou et al., 2006)**

Single objective decision making methods evaluate available alternatives with uncertain outcomes under a single objective situation (Howard and Matheson, 1984).

Decision support systems refer to any interactive, flexible and adaptable software system that integrates models, databases and other decision aiding tools (Turban, 1995).

Multi criteria decision making (MCDM) methods allow decision makers to rank or choose alternatives on the basis of several (more than one) evaluation criteria. Decisions in this sense are made based on trade-offs or compromises among a number of conflicting criteria (Colson and de Bruyn, 1989). The two main branches of MCDM methods include multi-objective decision making (MODM) and multi-attribute decision making (MADM) methods. MODM methods are mathematical programming models in which a set of conflicting objectives (more than one objective) are to be optimized subjected to a set of mathematically defined constraints. Similar to other mathematical programming methods, the sets of alternatives are virtually infinite in MODM methods and therefore these methods are usually referred to as “design” methods (Hwang and Masud, 1979).

Multi-attribute decision making (MADM) methods rank a finite number of feasible alternatives based on the characteristics of each attribute and preferences of the decision makers. A MADM model is a procedure that specifies how the relevant information is to

be processed in order to arrive at a “choice.” Performance of alternatives over defined attributes is usually shown in the form of a decision matrix. For a problem with  $n$  attributes ( $C_j, j = 1, \dots, n$ ) and  $m$  alternatives ( $A_i, i = 1, \dots, m$ ), the decision matrix is as follows:

$$D_{m \times n} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

Where,  $x_{ij}$  is the performance of the  $i^{\text{th}}$  alternative on the  $j^{\text{th}}$  attribute. The optimum solution is  $X^* = (x_1^*, x_2^*, \dots, x_m^*)$ , where  $x_i^* = \max_j U_i(x_{ij}), j = 1, 2, \dots, n$ , and  $U_i(\cdot)$  indicates the value/ utility function of the  $i^{\text{th}}$  attribute. Since  $U_i(\cdot)$  is almost always non-monotonic (with the assumption that alternatives at hand are screened), the ideal solution for which all the attributes are at the optimum levels does not exist; Therefore in MADM models a “preferred” alternative is sought. A pre-assumption in using MADM models is that alternatives are screened. In the screening step, all the alternatives that are infeasible, dominated (feasible alternatives that have poor performance in all the attributes compared to other alternatives), and non-satisfying (feasible alternatives that do not satisfy a minimum level in an attribute) are omitted from the list of alternatives. Different MADM models use different logic (usually based on human behavior principles) in order to define how the alternatives are preferred over each other based on Decision Maker’s (DM) preferences. (Hwang and Yoon, 1981).

The first attempt of MADM ranking can be found in the study of Churchman et al. (1957). They used the simple additive weight (SAW) method in a MADM problem of enterprise investment schemes selection. The SAW method calculates a single value for each alternative which is the sum of the alternative’s performance by the relative importance of each criterion. Simple multi-attribute rating technique (SMART) uses the simple additive weight (SAW) method to obtain total values for individual alternatives, helping to rank them according to their order of preference (Edwards, 1977; Edwards and Barron, 1994). A variation of the SAW method is the Weighted Product Model (WPM) in which the score of an alternative is calculated based on multiplication of alternative’s

performance to the power of relative weight of the corresponding criterion (Triantaphyllou, 2000). Based on the hierarchical decomposition of decision making problem, Saaty (1977) proposed the method of AHP. This method decomposes decision-making related elements into a hierarchy consisting of an overall goal, a group of alternatives for reaching the goal, and a group of criteria that relate the alternatives to the goal. Benayoun et al. (1966) proposed the outranking approach and based on this approach developed the ELECTRE. The ELECTRE method strengthen the outranking relationship among alternatives by developing concordance and discordance matrices which represent how each alternative outranks other alternatives or is outranked by others. This method subdivides the alternatives to ones that outrank other alternatives the most and get outranked by others the least until all the alternatives are ranked from best to worst. Since the original ELECTRE method may not reach a full ranking order, this method was later improved by Roy (1971,1991) to solve problems of discrete MADM. Most famous versions of the ELECTRE method include: ELECTRE I, ELECTRE IS, ELECTRE II, ELECTRE III, ELECTRE IV, and ELECTRE TRI (Figueira et al., 2005). From the outranking methods family, Brans and Vincke (1985) proposed the PROMETHEE method, which defines preference functions based on the differences between attributes among different schemes. The PROMETHEE method has several practical advantages over ELECTRE methods which include: (i) method calculations are simple and more transparent to decision makers, (ii) all the model parameters have real world meanings and make sense for decision makers, (iii) less calculation effort is required to attain the end result compared to that of the ELECTRE methods (Georgopoulou et al., 1998). Two versions of the PROMETHEE method, namely PROMETHEE I and II are mostly used. The later version assures a full ranking of decision making alternatives.

Although the list of MADM techniques is much more extensive, the foregone methods are the most famous and frequently used methods in the field of energy planning (Pohekar and Ramachandran, 2004). More detailed explanation of these methods can be found in (Triantaphyllou, 2000). For example other MADM methods include TOPSIS (technique for order preference by similarity to an ideal solution), proposed by Hwang and Yoon(1981), which uses ideal and anti-ideal solutions to find the best alternative,

considering that the chosen alternative should simultaneously have the shortest distance from the ideal solution as well as the longest distance from the anti-ideal solution. Also, variation of the MADM methods has been introduced over time, by combining different theories and methods. The use of linguistic fuzzy numbers in MADM methods is among the mostly studied combinations. Baas and Kwakernaak(1977) discussed the application of fuzzy sets in MADM. Chen (2001) proposed fuzzy extensions of the TOPSIS method. Siskos et al. (1984) introduced fuzzy sets into ELECTRE, and Goumas and Lygerou (2000) introduced fuzzy sets into PROMETHEE.

It should be noted that different multi attribute decision making methods applied to the same problem may result in different rankings and results (Gershon and Duckstein, 1983). This is due to the fact that each method utilizes a different mathematical procedure to draw the alternatives ranking and is formed based on a different decision theory principals. The results of MADM methods should be looked at as a negotiation basis in the decision making process rather than tools for making rigid decisions. Therefore, these methods are often referred to as “decision aid” rather than “decision making” tools (Zanakis et al., 1998). The importance of decision aid techniques is in their systematic way of articulating the decision-making process and offering insights for the involved stakeholders on conflicting issues in order to develop consensus about the best viable alternative.

Decision aid techniques integrate quantitative and qualitative information into a single output for ranking the alternatives considering a set of alternatives introduced by the decision makers and a set of criteria for comparing the alternatives.

The decision making process starts with a thorough definition of the decision to be made, its scope and boundaries. The legitimate stakeholders involved in the decision making process should be identified (Banville et al., 1998) and feasible alternatives to be considered should be developed (Kumar et al., 2006). One of the most important steps is to select the MCDM evaluation method which dictates what kind of data and information need to be gathered (Figueira et al., 2005). The final step is the evaluation phase which is

to evaluate the alternatives with the selected method, carry out the sensitivity analysis and present the results to the decision makers (Hobbs and Meier, 2000).

### **2.2.2. Multi attributed decision making in energy planning**

The two major evaluation approaches used in the energy planning field have been monetary and non-monetary methods (Nijkamp et al., 1990). Monetization methods such as Cost Benefit Analysis, Social Cost Benefit Analysis, Cost-Effectiveness Analysis, Willingness to Pay, and Willingness to Accept measure the cost or benefit of an energy plan or policy. These methods are based on the well developed theory of economic welfare and translate the tradeoffs into monetary values. However, the need to incorporate environmental and social values after the 1980s (Nijkamp and Volwahren, 1990), showed the inadequacy of these approaches in capturing the full range of impacts and complexity of issues in environmental and social issues (Browne et al., 2010). For example, the long term environmental impacts of exploiting an energy alternative or the value of a human life may not only be lost in the monetizing attempts, but also not be quantifiable in monetary terms (Hobbs and Horn, 1997). If the considered criteria for evaluating energy alternatives are limited to technical and economic performances of the energy alternatives, then techno-economic analysis and methods such as Net Present Value (NPV), Internal Rate of Return (IRR), etc. would be sufficient (Chau et al., 2009; Kumar et al., 2008). Conversely, when qualitative criteria such as “social and public health effects of energy alternatives” (Siskos and Hubert, 1983) come to play or the exact economic conversion factors of criteria are not available or generally acceptable, the application of MADM methods should be emphasized (Hobbs and Meier, 2000). In particular, when comparing renewable energy sources against each other and conventional fossil fuel sources, in which environmental performance and social aspects are more highlighted, non- monetary values are important. On the other hand, the complexity of energy problems in having several, incommensurable factors, and the existence of multiple stakeholders with subjective and/or conflicting interests and objectives, enhanced the application of Multi Criteria Decision Aid methods in the area of energy planning.

The strengths of MADM in the energy planning decision making field compared with reductionist techniques such as monetization methods are as follows (Munda, 2006):

- It is useful for resolving conflicting interests.
- It promotes public participation and bottom–up democracy through transparent decision-making.
- It can be used for heuristic purposes, where the objective is process-oriented rather than results-oriented.
- It provides a single decision output, which aggregates individual impacts.
- It facilitates multi-disciplinarily and can be adapted to include biophysical, socio-economic and political criteria.
- It can be modified to assign weights to criteria using stakeholder’s input, depending on the software or techniques used.
- It allows for analysis of incommensurable and uncertain criteria.
- It can be used to complement reductionist monetary or biophysical measures in a more holistic approach.
- It allows including criteria that are difficult to monetize or measure.
- It can aggregate both qualitative and quantitative information.

The use of MADM methods also benefits the stakeholder groups involved in the decision making processes concerning energy issues by:

- Structuring the decision process,
- Displaying tradeoffs between criteria,
- Helping stakeholders to articulate and apply their value judgments regarding suitable tradeoffs,
- Facilitating communication and set a basis for negotiation, and
- Facilitating public participation in energy decisions (Higgs et al., 2008; Hobbs and Horn, 1997; Hobbs and Meier, 2000).

To date, a number of literature survey papers have been published that review application of decision analysis techniques in energy related issues (Corner and Kirkwood, 1991; Keefer et al., 2004), energy and environmental modelling (Huang et al., 1995a; Zhou et al., 2006), and sustainable energy planning (Pohekar and Ramachandran, 2004; Wang et al., 2009). Pohekar and Ramachandran (2004) reviewed more than 90 papers in which MCDM had been used for energy planning problems and stated that Multi Attribute Decision Making (MADM) methods got increasing attention in renewable energy planning especially after 1990. The most famous and widely used methods were Weighted Sum Model, Weighted Product Model, Analytic Hierarchy Process (AHP), ELECTRE, PROMETHEE, and TOPSIS. Zhou et al. (2006) completed the literature survey study initially conducted by Huang et al.(1995a) and reported that among various decision analysis methods used for energy and environmental modelling, MCDM methods got increasing popularity. Especially, energy-related environmental studies were the most important application area of these decision analysis techniques (Zhou et al., 2006). They also stated that although AHP was the most widely used method in the literature, the number of studies carried out based on the outranking methods (ELECTRE and PROMETHEE) had the fastest growing rate in this field (Zhou et al., 2006). Polatidis et al. (2006) reviewed the selection criteria for multi criteria decision making methods in the energy planning field based on the level of compensation that various methods allow and the ability in incorporating the sustainability concept in different methods. They state that the outranking methods (PROMETHEE and ELECTRE) were suitable for application in energy planning field especially when renewable energy options were among the alternatives. This is due to partial compensability of outranking methods compared to multi attribute utility theory methods such as SAW and AHP. The review of application areas of multi criteria decision analysis methods for energy planning problems reveal that majority of the studies are at a high planning level such as a regional or national level, while less research is available on local energy systems with multiple energy carriers (Loken, 2007). The assessment of energy alternatives performance at the local level would include local people's concerns about the local impacts of the energy facility (Alanne et al., 2007; Jaber et al., 2008; Mroz and Thiel, 2005; Polatidis and Haralambopoulos, 2004). Apart from structuring the

decision making process, the MADM analysis can help local energy projects to increase public confidence in the decision outcome as public values and concerns would be directly reflected in the decision process (Hobbs and Horn, 1997).

Table 2-1 summarizes previous studies using SAW, AHP, PROMETHEE, and ELECTRE methods in selecting the best alternative from a set of feasible options in the energy planning field. The decision making criteria used in the studies reported in Table 2-1 include:

1. Economic: installation cost, operating cost, macro-economic effects, commercial viability, specific investment cost, fuel cost, maintenance cost, payback period,
2. Technical: efficiency, supply security, reliability, safety, fuel availability, consumer convenience, service life,
3. Environmental: GHG emissions, sulphur emissions, nitrogen oxides emissions, particulate emissions, land use, usage of environment as emissions and wastes sink or resource pool, conservation of natural ecosystems, accidents, long-term risks,
4. Political/social factors: political legitimacy, emanating effects on other areas of society, public acceptance, energy security, centralization, employment, use of local resources, education, research and development.

It should be noted that some energy planning studies are based on other multi criteria decision making methods. One of the major application areas of MCDM methods has been to choose the energy source and technology alternative from a set of available renewable and conventional options. When compared to conventional fossil energy sources, renewable technologies may be less favorable in terms of economic and technical aspects. The advantage of renewable energy options include environmental as well as social benefits which should be incorporated in the decision making process alongside the economic and technical factors.

Review of the application of multi-attribute decision making methods in the energy planning problems reveals the benefits of these methods in: a) incorporating environmental and social factors into the decision, b) engaging various stakeholders in

the decision making, c) framing the decision making process, and 3) clarifying decision tradeoffs. Multi-criteria methods, when renewable energy options are present, are more often applied in the European cases. This might be due to higher environmental awareness in these countries and the need to reflect on the public concerns over environmental impacts of the energy decisions.

The choice of the multi-criteria decision making method is to some extent dictated by the features of the decision making problem at hand. For example, the AHP method which is found to be the most popular method in the energy decisions is more suitable for decision problems with a high number of decision making criteria. In this regard the key feature of the AHP method in breaking down the decision criteria into hierarchies, and applying the pair wise comparison concept makes it easier for decision analysts to extract experts and stakeholders' preferences. However, methodological complexity of this method reduces its transparency to the decision making group.

The outranking methods, ELECTRE and PROMETHEE, have received increased attention in the energy decision problems field. The outranking concept which these methods are based on, does not allow for compensation among economic criteria and environmental or social values which is a strong feature for these methods application in the energy problems. The PROMETHEE method is a more transparent method compared to ELECTRE and requires less mathematical endeavor to reach the final ranking of the alternatives.

**Table 2-1: Energy planning studies using SAW, AHP, PROMETHEE, and ELECTRE multi attribute decision making methods**

| <b>Author(s)</b>           | <b>Year</b> | <b>Method</b> | <b>Application area</b>     | <b>Country</b> | <b>Description</b>  |
|----------------------------|-------------|---------------|-----------------------------|----------------|---|
| Afgan and Carvalho         | 2002        | SAW           | Energy source selection     | Portugal       | Various energy sources including: coal, solar, geothermal, biomass, nuclear, PV solar, wind, ocean, natural gas, and hydro, for a power plant were compared.  |
| Renn                       | 2003        | SAW           | Energy policy appraisal     | Germany        | Four energy scenarios for energy conservation and waste heat utilization in Germany were ranked based on group judgments of multi stakeholders such as unions and public utilities.   |
| Liposcak et al.            | 2006        | SAW           | Energy policy appraisal     | Croatia        | Three energy policies regarding promotion of combined heat and power generation systems were compared.  |
| Patlitzianas et al.        | 2007        | SAW           | Renewable energy assessment | EU accession   | The operational environment of renewable energy producers' in 14 EU accession countries was assessed based on quantitative and qualitative indicators.  |
| Saaty et al.               | 1977        | AHP           | Energy policy appraisal     | U.S.A.         | Electric utility policy options were compared using hierarchical analysis of strategies.  |
| Hämäläinen and Seppäläinen | 1986        | AHP and ANP   | Energy source selection     | Finland        | Three possible electricity generation scenarios: nuclear, coal fired, or decentralized plants and imports, were compared.   |
| Hämäläinen                 | 1990        | AHP           | Energy policy appraisal     | Finland        | The decision making issue between two groups, one in favor and one against of construction of a new nuclear power plant was structured based on AHP method and the results helped DMs during the debate.                    |
| Hämäläinen and Karjalainen | 1992        | AHP           | Energy source selection     | Finland        | Different alternatives for energy production based on societal and environmental criteria were compared..   |
| Karni et al.               | 1992        | AHP           | Energy policy appraisal     | Israel         | Policy alternatives for possible energy sources were structured and preferences of decision makers were extracted using various methods including AHP. The issue of ranking instability using various methods was observed. |

**Table 2-1: Energy planning studies using SAW, AHP, PROMETHEE, and ELECTRE multi attribute decision making methods (continued)**

| <b>Author(s)</b>              | <b>Year</b> | <b>Method</b> | <b>Application area</b>     | <b>Country</b> | <b>Description</b>  |
|-------------------------------|-------------|---------------|-----------------------------|----------------|---|
| Ramanathan and Ganesh         | 1995        | AHP           | Energy resource allocation  | India          | The best allocation of energy sources for various household energy requirements has been identified. The energy alternatives included natural gas, fuelwood, solar, biogas, and grid electricity. |
| Akash et al.                  | 1999        | AHP           | Energy source option        | Jordan         | Electric power generation based on possible options of fossil fuel, nuclear, solar, wind, and hydro were ranked.  |
| Aras et al.                   | 2004        | AHP           | Site selection              | Turkey         | Several possible sites for construction of a wind observation station which measures wind speed and path were ranked.   |
| Kablan                        | 2004        | AHP           | Energy conservation         | Jordan         | Several energy conservation policies such as fiscal incentives, public training, regulation and legislation, and R&D programs were ranked.  |
| Pilavachi et al.              | 2009        | AHP           | Technology option selection | Greece         | Nine electrical power generation options using natural gas or hydrogen as fuel were ranked based on economic, technical and environmental factors.  |
| Goumas and Lygerou            | 2000        | PROMETHEE     | Site selection              | Greece         | Four low enthalpy geothermal field exploitation scenarios in a rural area were ranked.  |
| Haralambopoulos and Polatidis | 2003        | PROMETHEE     | Renewable energy assessment | Greece         | A group decision making framework for development of geothermal resource was structured.  |
| Diakoulaki and Karangelis     | 2007        | PROMETHEE     | Energy policy appraisal     | Greece         | Four electricity system expansion scenarios for meeting the future electricity demand were ranked.  |
| Madlener et al.               | 2007        | PROMETHEE     | Energy policy appraisal     | Austria        | The sustainability of several national strategies for diffusing renewable energy source for heat and electricity generation were compared.  |
| Cavallaro                     | 2009        | PROMETHEE     | Technology selection        | Italy          | The purpose of the study was to assist multiple decision making bodies rank various options for development of concentrated solar thermal technology based on their reflected preferences.        |

**Table 2-1: Energy planning studies using SAW, AHP, PROMETHEE, and ELECTRE multi attribute decision making methods (continued)**

| <b>Author(s)</b>               | <b>Year</b> | <b>Method</b> | <b>Application area</b>     | <b>Country</b>             | <b>Description</b>  |
|--------------------------------|-------------|---------------|-----------------------------|----------------------------|---|
| Siskos and Hubert              | 1983        | ELECTRE       | Energy source selection     | France                     | Six energy chains: oil, coal, nuclear, solar thermal plants, and solar photovoltaic were compared from the social and public health point of view.                                    |
| Barda et al.                   | 1990        | ELECTRE       | Site selection              | Northern African countries | Three suitable sites for construction of thermal power plants in northern part of Africa were ranked.   |
| Georgopoulou et al.            | 1997        | ELECTRE       | Energy policy appraisal     | Greece                     | Several electrical power generation strategies were assessed in a multi-stakeholder group decision making framework in order to meet the future demand of the Crete Island in Greece. |
| Beccali et al.                 | 2003        | ELECTRE       | Energy policy appraisal     | Italy                      | Three action plan scenarios for diffusion of renewable energy sources at the regional level were assessed in order to determine the best set of strategies.                           |
| Neves et al.                   | 2008        | ELECTRE       | Energy policy appraisal     | Portugal                   | Various energy efficiency initiatives were compared in terms of quantitative as well as qualitative indicators such as customer welfare, employment, economic benefits, etc.          |
| Papadopoulos and Karagiannidis | 2008        | ELECTRE       | Energy policy appraisal     | Greece                     | The achievable penetration of renewable energy sources into an insular system for the purpose of electricity generation was determined.   |
| Madlener et al.                | 2009        | ELECTRE       | Renewable energy assessment | Austria                    | The relative performances of 41 biogas plants in Austria were determined in terms of economic, environmental and social indicators.   |

### **2.3. Techno-economic assessment of district energy systems**

In a techno-economic assessment of an energy production system, technical requirements and specification are considered for the purpose of identifying economic evaluation of the project (Chau et al., 2009). The objective of this section is to evaluate economical viability of renewable energy options compared and key factors in economic success of these technologies. The economic factors and indicators considered in the techno-economic study of an energy production system may include (Wang et al., 2009):

- Investment cost: represents all the initial costs associated with the development of the plant including the purchase of mechanical equipment, technological installations, construction activities, connections to the grid, district heating network, drilling activities in the case of geothermal energy, and engineering services. Initial investment costs normally occur once during the service life of the energy production system.
- Operating and maintenance costs: major components of Operating and Maintenance (O&M) costs include labour wages, energy and fuel expenses, and overall maintenance expenses. These expenses are recurrent items during the service life of the energy production system.
- Service life: The expected lifetime or the acceptable period of service use for an energy production system defines the service life of the system.
- Discount, depreciation, and tax rates: for the sake of economic evaluations various rates should be set including discount rate, depreciation rate, and tax rates. The discount rate represents the rate at which the investment should be amortized. The value of buildings and equipment depreciate over time. Taxes are charged on purchases, property, energy sales, and revenues at various rates which should be explicitly considered.
- Net Present Value (NPV): The NPV method measures the present value of all the cash flows during the service-life of the energy production system. NPV is one of the widely used methods for capital budgeting and evaluation of economics of energy production systems.

- Payback period: The simple payback period of an energy project is the period of time required for the return on the investment to “repay” the sum of the original investment and all other expenses.
- Levelized cost of produced energy: This is the cost of produced heat from an energy producing facility over the service life of the plant. The levelized cost of produced energy, which can be in the form of electricity, heat, or both, is calculated by dividing the total present value of initial and O&M expenses by the total estimated produced energy during the service life of the plant.

Bridgwater (1995) studied the economics of power generation from biomass gasification technology. At the time when this study was carried out, gasification technology was still an immature technology tested only in laboratory. The estimated capital cost of the technology was remarkably higher than other conventional options (estimated at US\$35 million for a 10 *MWe* plant) mainly due to immaturity of the technology option. Although economic revenues of the biomass gasification were not evaluated, it was concluded that increasing system’s capacity, processing low-cost materials such as waste and residue, or relying on fiscal incentives such as carbon tax could improve the economic viability of the biomass gasification system.

Gustavsson (1997) studied economic performance of cogeneration, power only and heat only plants using forest biomass, natural gas, oil, coal, and electric heat pumps (using refused industrial heat). The results showed that cogeneration was less costly than the separate production of electricity and heat. In the heat producing plants, the heat pump option was the economical option compared to the boiler alternatives. It was also concluded that wide spread installation of heat-only biomass boilers for district heating could be seen as an obstacle for investments in the potential cogeneration plants in Sweden. The investment on CHP systems should either be directed towards retrofitting the existing heat-only plants or otherwise accommodate enough heat demand from buildings that are not already served by the existing plants. Although cogeneration plants are more energy-efficient and less costly, low electricity prices in the country has limited the economic competitiveness of cogeneration too.

In a similar study, profitability of investment in small-scale biofuel fired CHP plants with the possibility of using the produced heat for district heating in Finland was studied (Keppo and Savola, 2007). It was concluded that large biofuel fired CHP plants were economically feasible. At the small scale level, based on the study of three possible cases, CHP plants required higher specific investment (investment per unit of energy produced) than biofuel fired boiler option for heat production. Therefore, investment in CHP plants was less attractive than boiler options. Also the economic competitiveness of CHP plants was found to be very sensitive to the economic factors such as future electricity prices and discount rates. However, trading emissions, rising electricity prices, and increasing biomass generated electricity could be viewed as potential strategies for making CHP economically attractive in the long run.

The cost of heat production or cogeneration of natural gas and wood chips in a district heating plant in Sweden was analyzed by Sundberg and Henning (2002). It was concluded that investment in a CHP system would not be profitable, except for the case when the electricity price would rise by more than 40%. In the current situation and fuel and electricity price projections, investment in a woodchip fired hot water boiler was recommended. However, upon receiving government grants for biomass fired CHP installation, or purchasing biomass at a slightly lower price than that of woodchips, a biomass fired steam cycle system would well compete with a hot water boiler.

Rogner (1993) studied the economic performance of district energy system versus decentralized heating options for two specific locations in Toronto. The two technology scenario options considered for decentralized systems were either an average efficiency natural gas boiler or the best available technology. The technology options for district heating system were either a centralized natural gas boiler or natural gas based CHP. Based on the levelized annual cost of options over life cycle of the systems, Rogner (1993) concluded that district heating systems even without economic or environmental subsidies had better long-term economic performance than decentralized systems. Between the two technology options available for generating district energy, the CHP system had lower levelized cost than the central boiler option. This was due to electricity sales possibility in the case of the CHP system.

In a detailed techno-economic study, Bridgwater et al. (2002) calculated the cost of producing electricity from biomass power generation using gasification and fast pyrolysis technologies at capacity ranges of 1-20 *MWe*. The developed economic model considered all the system components from fuel pretreatment to electricity delivery to the grid, including: feed pretreatment, combustion, atmospheric and pressure gasification, fast pyrolysis with pyrolysis liquid storage and transport and diesel engine or turbine power generation. Moreover, effects of reduced capital cost in the future for these novel technologies were investigated. They concluded that these novel technologies are not able to compete against the well established combustion and steam cycle technologies. Typical characteristics of novel technologies such as high capital cost, high labour requirement, and low reliability are the major contributing factors to low competitiveness of these technologies. Reduced capital cost advantage of the fast pyrolysis and diesel engine configuration, however, suffers from low system efficiency especially at high capacity ranges. It was concluded that at the small scale, in the long run and with early development of demonstration pilot plants, the fast pyrolysis and diesel engine configuration could produce electricity at lower cost than any other biomass to electricity system.

Rentizelas et al. (2009) compared economic performance of two biomass conversion technologies (gasification and Organic Rankine Cycle, ORC) to be used in a district tri-generation (heating, cooling, and power) plant in Greece. They concluded that ORC required notably lower capital, operating and maintenance costs than the gasification technology. However, the gasification technology had more electricity sales revenue obtained from its higher power-to-heat ratio (power output to heating energy output) and that would offset its higher costs.

The potential of heat and power co-generation (CHP) from agricultural residues in the island of Crete, Greece, was studied by Bakos et al. (2008). The economic viability of the proposed agricultural-based CHP was studied based on a techno-economic model which considered feedstock price and its availability as well as technical, operational, and economic parameters of the power plant. From an economic viability perspective, potential electricity generation of 360 *GWh/yr* and heat production of 510 *GWh/yr* were

achievable. However, investment consideration barriers require higher investment subsidies on biomass systems in order to enable earlier installation of biomass CHP plants in that region.

Lazzarin and Noro (2006a) studied the possibility of connecting an established Heating, Ventilation, and Air Conditioning (HVAC) system with two natural gas boilers and a natural gas engine heat pump to a district heating network in Vicenza, Italy. They concluded that the investment and operating costs associated with the proposed connection were not economically beneficial to end users and would result in higher energy bills for residents. In a similar study, Lazzarin and Noro (2006b) conclude that heat and power generation with natural gas technologies in district energy systems, may not always be the best alternative from the overall efficiency point of view. However, from an economical perspective, because of lower natural gas taxation for CHP plants, district energy system is more attractive; especially when high efficiency CHP systems, such as Gas Turbine Combined Cycle-GTCC, are employed.

Klugman et al. (2008) studied the possibility of integrating a pulp mill into a regional district heating market in central Sweden. The possible expansion scenarios for heat production included: process integration (using excess heat instead of steam production), direct mill sewage heat recovery, mill sewage heat pump, and adding a condensing unit to the existing back-pressure turbine. It was concluded that with process integration, the steam production requirement could be avoided and the bark burning steam boiler could be shut down, which would add bark sales revenue to the plant. Moreover, the economic benefits of the process integration scenario could be coupled with either sewage heat recovery options especially when electricity generation was considered during non-peak heating periods. Sensitivity analysis of the results showed little influence of energy prices, except for when the electricity sales prices was considered in the option with electricity generation possibility.

The techno-economic assessment of a horizontal loop geothermal heat pump option in Turkey showed economic and efficiency advantages of this heat source over conventional heat sources in the region (electric resistance, fuel oil, liquid petrol gas,

coal, oil ) except for natural gas (Esen et al., 2006). Easy access to nearby natural gas reservoirs and inexpensive natural gas equipment result in better economics of natural gas heat source when compared to the geothermal option.

Exploitation of a geothermal field for district and greenhouse heating purpose in the region of Traianoupolis Evros, Turkey, was examined for potential socio-economic benefits (Karytsas et al., 2003). In terms of Net Present Value (NPV), Internal Rate of Return (IRR), and simple payback period, it was found that greenhouse heating was an attractive investment with or without government support. The geothermal district heating in this area was found to be marginally profitable, while governmental support would make it an attractive investment. The cost of produced energy over the service life of the system (without government support) was US\$0.24 per *KWh* for district heating and US\$0.013 per *KWh* for greenhouse heating.

Erdogmus et al. (2006) investigated the cost of geothermal district heating in Balcova–Narlidere, Turkey. The economic calculations based on zero Internal Rate of Return (IRR) identified that the energy cost for customers would be at least US\$55.0 for an average 100 m<sup>2</sup> household. If energy prices lower than this was sought, governmental subsidies should be included; otherwise the investment would not be attractive.

The utilization of air source heat pumps for hot water production in large buildings such as hospitals in central parts of South Africa was found to be advantageous over electrical heating (Meyer and Greyvenstein, 1992). The considered economic factors for the sake of comparison between the two options included: payback period, net present value and internal rate of return.

Chau et al. (2009) studied the economic feasibility of replacing natural gas boilers with wood pellet or wood residue fired boilers for heat production at greenhouses in BC, Canada. The proposal could generate positive net present value for greenhouses for both wood biomass cases even when the costly electro-static precipitator was installed for removal of particulates from the flue gas.

The review of the economic studies of the renewable technology options shows that these technology options are becoming more economically viable as the technology advances. Although the level of advancement and diffusion of renewable technology options vary, biomass based technologies have advanced to the point where they have become attractive compared to conventional fossil burning technologies. The governmental subsidies and financial support might still play an important factor in economic success of bioenergy technologies. The early adoption of emerging renewable technology options require higher governmental support compared to more established technology options. Economical sensitivity of renewable technology options is influenced by fossil fuels and electricity prices variation; in this regard such policy measures as carbon tax on fossil fuels can play a role in selecting renewable options.

#### **2.4. Life-cycle assessment of energy systems**

Life cycle assessment (LCA) and ecological foot printing are quantitative methods used to assess the environmental impacts of an energy producing plant (Curran et al., 2005).

Ecological foot printing calculates land and water areas that are necessary to supply a specific economic unit with material and energy as well as to cope with its waste are determined (Stoeglehner and Narodslawsky, 2008). This method was first introduced by (Rees, 1992) and further developed by (Wackernagel and Rees, 1995). A comprehensive description of the footprint model is included in (Monfreda et al., 2004).

The LCA methodology considers potential environmental impacts of a product from raw material and resource extraction, to commodity manufacturing, use, maintenance and end of life. LCA study was first carried out on comparison of plastic and glass beverage containers for Coca Cola in 1969. The results of this LCA study indicated preference of plastic rather than glass containers when life cycle resource and energy consumption were considered. Most LCA studies in the era of early development of this method were driven by the oil crisis of 1970's and landfill overcrowding of 1980's (LeVan, 1996). The lack of a consistent methodological pathway to calculate the material and energy flows

and omission of conversion to subsequent environmental impacts made the replication of LCA studies of this era impossible (LeVan, 1996). The acceptance of LCA results of this era was greatly undermined by issues related to the validity of LCAs performed under marketing pressures and the manipulation of results by practices such as inconsistent product system boundary definition (Klopffer, 2005). The “Code of Practice” published by the Society of Environmental Toxicity and Chemistry (SETAC) standardized the life cycle assessment by separating it into three distinct methodological components. These are the goal and scope definition, life cycle inventory, and life cycle impact assessment (Consoli et al., 1993). Afterwards, International Standard Organization (ISO) developed a set of framework and guidelines for standardization of conducting LCA studies. These series of standards were chronologically updated until the last versions of ISO 14040:2006 and ISO 14044:2006 were published (International standard ISO 14040, 2006; International standard ISO 14044, 2006).

According to ISO standards, the LCA study consists of four components:

1. Goal and scope definition which defines the purpose of the study, study boundaries, the required data and information.
2. Life Cycle Inventor (LCI) which determines the entire life cycle emissions and resource consumption of the product under study.
3. Life Cycle Impact Assessment (LCIA) which evaluates the potential environmental burdens and impacts on human health associated with the developed LCI. Each impact indicator in this phase is calculated by multiplying the LCI values by characterization factors that relate the flows in the LCI to anticipated impacts (Pennington et al., 2004).
4. Interpretation phase in which the results are analyzed, conclusions are drawn, limitations are clarified, and recommendations are provided.

Critics of the LCA methodology are typically concerned with the impacts of inventory data quality, methodological choices in relation to time aspects, allocation, characterization, weighting methods, and uncertainties in describing the real world would have on the results (Finnveden, 2000). Ayres (1995) state that careful quantitative study

and analysis of material flows and transformations, and energy fluxes are valuable exercises in inventory data development. However, complete range of specific data required for inventory development is seldom available. Therefore, in many studies theoretical process descriptions and formulation, “confidential”, or unverifiable data are used. On the impact assessment side three issues in the current debate of LCIA can be highlighted (Pennington et al., 2004):

- Assessing impacts for the marginal production, i.e. incrementally based on one extra unit of production, or averaged over the total impacts of all functional units.
- Identifying the goal of finding environmental impacts and considering the uncertainty issue in modelling the complex cause-effect chains of environmental impacts which start with chemical emissions. For example, global warming potential impact category can be properly reported as a “midpoint” effect, as CO<sub>2</sub> equivalent, instead of the harm caused by the global warming impact.
- Considering limitations of impact estimation based on spatial and time frame diversity. Resources and emissions come from and go to a variety of landscapes over varying periods of time which limits applicability of impact estimation.

It should be noted that LCA results should not be generally used for showing that one product is environmentally preferable to another one, especially for rigid policy actions (Finnveden, 2000). In spite of LCA methodological imperfection, LCA study has the utility (Ayres, 1995) for discovering underlying environmental implications of goods and services.

The LCA method has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources. Depending on the scope of the LCA study, life stages of the energy production system may include all or part of: 1) fuel production and transportation to the plant, 2) facility construction, 3) facility operation and maintenance, and 4) dismantling (Mann and Spath, 2001). The objective of this section is to review LCA studies that consider life-cycle environmental burdens associated with energy production from biomass energy sources and in the district energy application.

Mann and Spath (2001) carried out life cycle assessment of biomass co-firing in a coal fired power plant when 5% and 15% of the heat input was replaced by wood residues (waste wood, mill residue, urban wood residue). The life cycle inventory included all stages from fuel preparation (surface coal mining and wood residue acquisition), to material production, manufacturing of co-firing related equipment, coal and biomass transportation, grid electricity production in upstream processes, and the avoided processes of wood residue mulching and landfilling. The Tools for Environmental Analysis and Management (TEAM) software has been used in order to model the inventory and compare the environmental benefits of co-firing with the case of 100% coal firing. It was concluded that in terms of *MWh* of electricity produced by the plant, co-firing reduced airborne emissions ( $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{NO}_x$ , non-methane hydrocarbons, particulates, and carbon CO), total system energy consumption, resource consumption (non-renewable fuel consumption and limestone equivalent), and solid waste generation. It was also shown that applying different wood waste management regimes would reduce  $\text{CO}_2$  effects of biomass co-firing.

The life cycle assessment of willow energy crop with wood residue blend co-fired at 5% and 10% energy input rate in a coal-based power plant demonstrated reductions in many of the environmental impacts of the facility (Heller et al., 2004). The incremental life cycle environmental impacts of avoided coal surface mining, transportation, and combustion and embraced biomass production, cultivation, and transportation, and facility modification were estimated by the TEAM software. It was shown that electricity generation from willow biomass was nearly GHG free (40-50 kg  $\text{CO}_2/\text{MWh}_e$ ). Also, co-firing of willow/wood residue blend biomass resulted in reductions of criteria air pollutants of  $\text{SO}_2$ , Hg, and  $\text{NO}_x$ .

Life cycle environmental impacts of integrated gasification combined cycle (pressurized fluidized bed) for power generation using poplar short rotation forestry biomass was investigated by Rafaschieri et al. (1999). The inventory of energy, raw material consumption and polluting emissions of biomass production (nursery, short rotation forestry, plantation, harvesting), processing and transportation to the plant were obtained from experimental cases, while energy consumption and pollutions from energy

production systems were modeled based on thermodynamic simulation models. In order to estimate the aggregated environmental impact of the life cycle inventory, the Eco-indicator 95 method was used which categorizes impacts into: environmental protection (GHG, ozone layer depletion, acidification, eutrophication), health safety (smog formation, toxic substances release), and resource depletion (solid waste production, energy consumption). It was concluded that the use of chemicals and fertilizers during biomass production phase caused the most negative environmental impacts. Also, utilization of air as oxidizer during gasification process caused 2 to 7 times less environmental impacts than the case of oxygen gasification. About 99% of the negative environmental performance of oxygen gasification was attributed to the electricity consumed for oxygen production. In order to reduce the life cycle environmental impacts of the process, Rafaschieri et al. (1999) suggested optimizing the applied fertilizer and biological antiparasitic solutions rate based on the biomass yield. Also, further carbon dioxide reductions could be achieved by switching from fossil fuels for machinery to bio-based fuels such as biodiesel. In this study, the life cycle inventory did not include power generation, facility construction or dismantling/ demolition.

Góralczyk (2003) assessed environmental impacts of producing 1 *GJ* renewable electricity using hydroelectric power, photovoltaic, and wind turbines in Poland. The results were also compared to environmental impacts of coal, oil, and natural gas fired power generation. The environmental impacts of various life stages of energy source options included contribution of power plant construction, operation, and waste disposal at each power plant. The results of this study showed that aggregated environmental impacts of fossil fuel options in terms of global warming potential, resource depletion, acidification and eutrophication, was remarkably higher than those of the renewable source options. Therefore, implementing energy management measures to reduce the share of fossil fuels and increase renewable-based electricity was recommended to Polish authorities in order to preserve resources and reduce emissions and pollutants.

Hondo (2005) developed the emission factors for the life-cycle greenhouse gases of nine power generation systems including coal-fired, oil-fired, Liquefied Natural Gas (LNG)-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and

solar-photovoltaic (PV). The life stages included: 1) plant construction and equipment production, 2) fuel acquisition, processing, and transportation (in case of fossil fuels and nuclear), geothermal wells drilling (for both exploration and production wells of the geothermal option), 3) facility operation, 4) storage, disposal, or decommissioning (nuclear) of waste. The ranking of considered options from the best to the worst was as follows: hydro (11), geothermal (15), wind- 400 kW type (20), nuclear-with fuel recycling (22), nuclear without fuel recycling (24), PV with a-Si panels (26), PV- p-Si panels (53), LNG-CC (518), LNG-fired (608), oil-fired (742), coal-fired (975). All the GHG emissions attributed to renewable sources were due to indirect emissions, while for fossil sources, direct CO<sub>2</sub> emissions caused the majority of the impacts.

Zhang et al. (2010) studied and compared the life cycle emissions (GHG, NO<sub>x</sub>, and SO<sub>x</sub>) of two coal generating stations (co-fired with wood pellets) and a natural gas combined cycle plant in Ontario, Canada. The considered life cycle stages in this study included fuel production, transportation activities, and facility operation. The material and energy inputs required for facility construction and dismantling or equipment manufacturing of energy systems were not considered. It was presumed these activities had lower life cycle environmental impacts than the operation of the facility. The results of this study showed that the greatest GHG reduction levels per kWh of electricity generated could be achieved by 100% utilization of wood pellets in a coal generating station. This scenario could reduce the GHG emissions of the facility by 91% and 78% of the current levels of coal fired and natural gas fired facilities, respectively. Also, replacement of coal with wood pellets would reduce NO<sub>x</sub> and SO<sub>x</sub> emissions of the facility by more than 40% and 75%, respectively. However, when considering the economics of the systems, the most cost effective GHG reduction scenarios were wood pellet co-firing or natural gas combined cycle.

Jungmeier et al. (1998) considered the entire life cycle environmental burdens of a 1.3 MW<sub>e</sub> biomass combined heat and power plant that generated 4700 MWh of electricity and 29,000 MWh of district heat annually in Austria. The life cycle stages included plant construction, wood fuel preparation (cultivation and harvesting, transportation, processing, storage), plant operation, and dismantling. They concluded

that for each environmental impact category, a specific life stage was the main contributor. For example, CO<sub>2</sub> emissions were higher during the plant construction phase because of concrete and steel production contribution; airborne emissions of CO and NO<sub>x</sub> were higher during the plant operation stage that resulted from combustion emissions, and soil emissions were higher during the dismantling phase.

Eriksson et al. (2007) compared the life cycle environmental impacts of a district heating system in Sweden considering alternative scenarios on fuel, heat only or combined heat and power, and waste management. The LCA inventory was built based on previously developed dataset of waste management systems in Sweden. The functional unit of the LCA was *MJ* of district heat produced by different scenarios. The impact assessment of the life cycle inventory inputs were based on three assessment methods: Ecotax 02 (which uses taxes and fees for various environmental impacts as social expressions of damages), EPS 2000, and Eco-indicator 99. Based on various impact assessment methods, they concluded when recycling of biomass was not an option, it would be more favorable to incinerate the biomass in a combined heat and power plant rather than dumping to a landfill.

The air borne emissions of CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> resulted from the energy consumed for production of material and equipment in off-shore wind farm as well as on-land wind farm were modeled by Schleisner (2000). The aggregation of emissions from utilization of energy in the form of electricity, heat, and transportation fuel for production, manufacturing, and transportation of 1 *kg* of equipment was calculated based on Danish emission factors for various processes users considered in the model. Allocation of the emissions to the production and transportation of various materials such as steel, aluminum, rebars, concrete, cables, were considered based on the weight of each material used in the production of on-land or off-shore wind farm for generation of 1 *GJ* electric power. The emissions for the off-shore wind farm were lower than those for the on-land wind. It was also shown that on a weight basis, 94% of the materials used in production of a wind turbine could be recycled.

Spath et al. (1999) studied the air borne emissions ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , particulates,  $\text{SO}_x$ ,  $\text{NO}_x$ ,  $\text{CO}$ , non-methane hydrocarbons) of coal fired power generation in the US. The system boundary of this study included upstream emissions from surface strip mining and underground long-wall mining of coal, associated truck, train, and barge transportation of coal, and power plant emissions. The results showed that the emitted  $\text{CO}_2$  during coal combustion at the plant consisted 98%-99% of total life cycle airborne emissions weight. Also, coal combustion resulted in the majority of  $\text{SO}_x$ ,  $\text{NO}_x$ , and  $\text{CO}$  emissions. Apart from coal combustion, it was found that limestone production, transportation, and use for flue gas clean-up accounted for more than half the non-coal  $\text{CO}_2$  emissions. Methane emissions from mining activity were the main source of this emission in the coal-fired power life cycle. Also, particulate emissions from limestone production were found to be higher than that of coal combustion and higher than federal air emission regulations. Findings of this research suggested that utilizing of other flue gas clean-up strategies than limestone scrubbing should be promoted as an emission reduction policy for coal-fired power plants.

The review of life-cycle assessment studies on energy generation from renewable energy options shows that various life stages may become significant for each energy option. For example, it was shown that co-firing of wood biomass options in coal burning power plants reduces the airborne emissions during facility operation. Co-firing of wood biomass reduces GHG emissions of the coal burning facilities as well as  $\text{SO}_x$  and  $\text{NO}_x$  emissions. For energy options that require extensive materials during construction, such as photovoltaic solar panels or wind turbines, the most significant contributors to life-cycle environmental impacts are those of the construction phase rather than the operation phase.

## **Chapter 3. A multi criteria approach to evaluate district heating system options\***

### **3.1.Synopsis**

The district heating system under study could exploit renewable energy sources such as wood pellets, sewer heat and geothermal. The type of energy to be used in a district energy system broadly identifies the characteristics of the system, such as the heating technology, system efficiency, capital investment, operating costs, system emissions, etc. The suitability of a district energy system, which depends on the type of energy source, characteristics of the system, and district's objectives and requirements, should be assessed carefully. Typically, different alternatives are available for district energy systems that should be evaluated based on economic, technical, environmental and social factors. These factors may be quantitative or qualitative. Moreover, the importance of these factors may be different for various stakeholder groups involved in the decision making, as they may have different and sometimes conflicting interests and objectives. The need to incorporate different factors and the viewpoints of various actors in the analysis has promoted the use of multi-criteria approaches in energy planning. These approaches provide a better understanding of the decision problem, help reaching a compromised decision, and facilitate the negotiation and communication among different stakeholders (Pohekar and Ramachandran, 2004).

This chapter focuses on the analysis of the decision making process of selecting district heating energy source<sup>1.4</sup>. The objectives sought in this chapter are to:

1. Identify and understand the major issues considered by various stakeholder groups for using wood pellets in district heating in Vancouver, BC.
2. Investigate how the stakeholders' perception about the energy source options for the district heating system affect the decision making process outcome.

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\* A version of this chapter has been published. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Melin, S. (2010), A multicriteria approach to evaluate district heating system options. *Applied Energy*, 87 (4): 1134-1140.

Based on PROMETHEE II multi criteria assessment method, four energy options of natural gas, biomass (wood pellets), sewer heat, and geothermal heat are ranked considering six important criteria. Two different scenarios (current situation and an ex-post analysis, that is analysis after the decision was made) are considered to show how the ranking of alternatives for stakeholder groups are affected by addressing and communicating the issues for involved stakeholder groups.

## 3.2. Methods used

### 3.2.1. The PROMETHEE method

The PROMETHEE II method is used in order to rank the energy sources available for the considered case based on stakeholders' preferences. The PROMETHEE method introduced by Brans and Vincke (1985) belongs to the group of outranking methods.

In order to better explain the PROMETHEE method, suppose a multi-criteria problem as:

$$\{f_1(a), f_2(a), \dots, f_h(a), \dots, f_k(a) | a \in K\} \quad 3-1$$

Where  $K$  is a (finite) set of possible alternatives, and  $f_h(a)$ ,  $h = 1, 2, \dots, k$ , is the value of alternative  $a$  for criterion  $h$ . Ideally, a decision maker is interested in finding an optimal alternative  $\hat{a}$  which dominates all other alternatives (has the highest value for all criteria compared to other alternatives) so  $f_h(\hat{a}) \geq f_h(a), \forall a \in K, \forall h$ . In general, such an optimal solution does not exist, and indeed the dominance relationship between the alternatives defined as:  $a$  dominates  $b$  iff  $f_h(a) \geq f_h(b), \forall h \in \{1, 2, \dots, k\}$  is poor between all the two-by-two alternatives. Outranking methods such as PROMETHEE focus on the dominance relationship between the alternatives.

Considering two alternatives  $a$  and  $b$ , the preference structure can be defined as:

$$\begin{cases} aPb & \text{iff } f_h(a) > f_h(b) \\ alb & \text{iff } f_h(a) = f_h(b) \end{cases} \quad 3-2$$

$aPb$  means that alternative  $a$  is preferred over alternative  $b$ , if alternative  $a$  is performing better than alternative  $b$  with regard to criterion  $h$ , and  $alb$  means that alternatives  $a$  and  $b$  are indifferent with regard to criterion  $h$ .

The PROMETHEE method gives a numerical value between 0 and 1 to the preference relationship in Equation 3-2 by introducing the preference function  $P(a,b)$  such that:

$$P(a,b) = \begin{cases} 0 & \text{if } f_h(a) \leq f_h(b) \\ p[f_h(a), f_h(b)] & \text{if } f_h(a) > f_h(b) \end{cases} \quad 3-3$$

Where  $0 < p[f_h(a), f_h(b)] \leq 1$ . For practical applications, it is then reasonable to assume that:

$$p[f_h(a), f_h(b)] = p[f_h(a) - f_h(b)] \quad 3-4$$

Let  $D_h(a,b)$  be the difference between alternative  $a$  and  $b$  for criterion  $h$  as shown in Equation 3-5:

$$D_h(a,b) = f_h(a) - f_h(b) \quad 3-5$$

Brans and Vincke (1985) recognized six types of preference functions that are most common in the real case situations. The “usual preference” function which considers absolute preference for any difference observed between two alternatives with regard to a certain criterion is used. In other words:

$$p[f_h(a), f_h(b)] = \begin{cases} 0 & \text{if } D_h(a,b) \leq 0 \\ 1 & \text{if } D_h(a,b) > 0 \end{cases} \quad 3-6$$

As an example, suppose that the levelized cost of energy production for option  $a$  is \$10 less than that for option  $b$ , then preference of alternative  $a$  over alternative  $b$  is 1 and preference of alternative  $b$  over  $a$  is 0.

Then, the PROMETHEE method uses the weighted preference index  $\pi(a,b)$  to give an integrated overall preference of alternative a over b, shown in Equation 3-7:

$$\pi(a,b) = \frac{\sum_{h=1}^k w_h P_h(a,b)}{\sum_{h=1}^k w_h} \quad 3-7$$

Where  $w_h$  is the relative importance of criterion  $h$ , which is defined by the decision makers. To build the outranking relation among the alternatives, PROMETHEE introduces three outranking measures for each alternative as follows:

- Outgoing flow  $\phi^+(a) = \sum_{x \in K} \pi(a,x)$ . The larger  $\phi^+(a)$ , the more alternative  $a$  outranks the other alternatives in the set  $K$ ,
- Incoming flow  $\phi^-(a) = \sum_{x \in K} \pi(x,a)$ . The smaller  $\phi^-(a)$ , the less alternative  $a$  has been outranked by other alternatives in the set  $K$ .
- The net flow is calculated as  $\phi(a) = \phi^+(a) - \phi^-(a)$ . PROMETHEE II considers the net flow for each alternative  $a \in K$  to find the complete ranking such that:

$$a \text{ outranks } b \text{ (aPb)} \quad \text{iff} \quad \phi(a) > \phi(b), \quad 3-8$$

$$a \text{ is indifferent to } b \text{ (aIb)} \quad \text{iff} \quad \phi(a) = \phi(b). \quad 3-9$$

In summary, to rank alternatives using the PROMETHEE II method, the analyst needs to identify the alternatives/ criteria matrix, which is called the decision matrix, the relative importance of criteria over each other, and the preference functions for each criterion.

### 3.2.2. The expected value method to determine criteria weights

The selected criteria usually do not have equal importance and different stakeholders may perceive their importance differently. Equal weighting and rank-order weighting methods are common methods in the multi criteria evaluation of energy projects (Wang et al., 2009). The equal weighting method ignores relative importance among criteria. In

rank-order weighting methods, the objective is to find the weight of each criterion in the form of  $0 \leq w_1 \leq w_2 \leq \dots \leq w_n$ , and  $\sum_{i=1}^n w_i = 1$ . Various ranking methods have been used for extracting and calculating relative importance of criteria in multi criteria evaluation of energy projects (Wang et al., 2009). In this study, the Expected Value method (Nijkamp et al., 1990) is used to extract the criteria weights. This method estimates the weights based on the decision makers' preferred ranking of the criteria. To better explain this method, assume that there are  $n$  criteria in the analysis which are ranked in ascending order of importance based on the decision maker's preference. Considering the general requirement of criteria weights where:  $0 \leq w_1 \leq w_2 \leq \dots \leq w_n$ , and  $\sum_{i=1}^n w_i = 1$ , we know that value of one of the weights, say  $w_n$ , equals:  $1 - w_1 - \dots - w_{n-1}$ . When no other information is available, it is reasonable to assume that probability density function of the weights is equal for all values. In other words, weights have uniform probability distribution function with the following structure:

$$f(w_1, \dots, w_{n-1}) = \begin{cases} c & \text{if:} & 0 \leq w_1 \leq \frac{1}{n} \\ & & w_1 \leq w_2 \leq \frac{1}{n-1} - \frac{w_1}{n-1} \\ & & \vdots \\ & & w_{n-2} \leq w_{n-1} \leq \frac{1}{2} - \frac{w_1}{2} - \dots - \frac{w_{n-2}}{2} \\ 0 & \text{elsewhere} \end{cases} \quad 3-10$$

It has been shown that  $c = (n-1)!n!$ . Now the expected value of the weights can be formulated as:

$$E(w_i) = \int_0^{1/n} \dots \int_{w_{n-2}}^{\frac{1}{2} - \frac{w_1}{2} - \dots - \frac{w_{n-2}}{2}} ((n-1)!n! w_i) d_{w_{n-1}} \dots d_{w_1} \quad 3-11$$

Where  $E(w_i)$  is the expected value of criterion  $i$ , and  $d_{w_i}$  is the derivative of the weight of criterion  $i$ . After appropriate integration (see (Nijkamp et al., 1990)) one arrives at the expected values for criteria weights  $w_i$  as:

$$\begin{aligned}
 E(w_1) &= \frac{1}{n^2} \\
 E(w_2) &= \frac{1}{n^2} + \frac{1}{n(n-1)} \\
 &\vdots \\
 E(w_{k-1}) &= \frac{1}{n^2} + \frac{1}{n(n-1)} + \dots + \frac{1}{n.2} \\
 E(w_k) &= \frac{1}{n^2} + \frac{1}{n(n-1)} + \dots + \frac{1}{n.2} + \frac{1}{n.1}
 \end{aligned}$$

Where  $E(w_i)$  is the expected value of the  $i$ th criterion (used as the weight for that criterion) and  $n$  is the number of criteria.

### **3.3. Analysis of the decision making process for the selection of the base-load heat source**

A district heating system to provide hot water to a newly developed community in the city of Vancouver, BC, was evaluated by the City. The supplied hot water would be used for space heating and providing hot water to the buildings within the community. The proposition was to install a 2.5 MW base-load system to provide the majority of the annual heat demand and to use a 10 MW low capital cost system with secure technology and fuel supply such as a natural gas boiler for peaking and backup (Compass Resource Management Ltd., 2006). Considering the available energy sources to energy centres in Vancouver, BC, four energy options of sewer heat, geothermal heat, biomass (wood pellets), and natural gas were evaluated by the City of Vancouver for the base-load energy system (FVB Energy Inc., 2006b).

During the feasibility study stage, several technical and economic studies including heat demand, base-load and backup system capacities, and cost analyses were performed by consultants and City departments (Compass Resource Management Ltd., 2006; FVB Energy Inc., 2006a; FVB Energy Inc., 2006b).

After the public announcement regarding the development of the district heating centre, various stakeholder groups became aware of different potential heat source options for the facility. It was during this stage that various stakeholder groups stepped

forward and got involved in the decision making process. The final decision was directly and indirectly influenced by various stakeholder groups involved in the decision making process. In general, three groups are identified who affected the decision on the base-load energy source for the district energy system including: (1) developer (including various departments within the City and consultants), (2) environmental groups, and (3) community representative groups (including the community and press). The developer was responsible for the design and construction of the district energy centre. Technical information about the considered energy sources were generated by the developer. This information was conveyed to the Greater Vancouver Regional District (GVRD) for obtaining required permits and the City council for final approvals. The GVRD and City Council then sought environmental and community representative groups' inputs on the issue. There had to be no objection from the environmental and community representative groups before GVRD and the City Council could issue permission on a selected energy source. Therefore, the decision authority situation in this case implied that the decision on the choice of the base-load energy source was affected by the environmental group and the community representative group.

In this research, the decision making process for choosing the heat source option for the district heating centre base-load was studied by reviewing of memoranda communicated among various stakeholder groups, media releases about the issue, City Council memoranda, and conducting a few open-ended interviews with the district heating project manager, an Environment Canada representative, and a Southeast Community Association representative. In this phase, the decision making criteria, importance of criteria for different stakeholders, and the values of alternatives were extracted based on the statements made by stakeholders.

The proposition by the developer group to consider wood pellets for district heating centre base-load was negatively received by the environmental and community representative groups. Several concerns regarding utilization and combustion of wood pellets at the district heating centre were raised. These concerns about the wood pellet option included (the gist of the concerns raised by various stakeholder groups can be best

seen in one of the last administrative reports sent to the City council by the developer group- which is shown in the Appendix):

1. Negative health impact associated with particulate matter emissions from wood combustion at the facility while natural gas or heat pump option would not impose such an impact,
2. The truck delivery of wood fuel would have undesirable impacts on local traffic,
3. Wood fuel should be hauled in from outside of the community, while local sources such as sewer or ground heat not be utilized,
4. Upstream and life cycle emissions associated with the wood fuel was not considered in the developer group's analyses. Especially, it has been argued that upstream environmental impacts associated with production and transportation of wood pellets could exceed those of other energy options and offset the GHG reduction advantage of this fuel option as a renewable source.

The developer group, however, was not able to properly address the issues raised by external stakeholder groups (community representative and environmental groups). Because of the project time limit, the next renewable option in terms of economical feasibility was recommended to the City Council for approval. The recommended option was the sewer heat recovery option and since it did not face any objection from environmental and community representative groups, it was approved for implementation.

### **3.4. Multi criteria decision making analysis of heat source option for the district heating centre base-load system**

In order to evaluate the effect of perception of various stakeholder groups on the decision making outcome, the decision making process described in the previous section was modeled as a multi-criteria decision making problem. Decision Lab. 2000 software (Brans and Mareschal, 2006) which offers the PROMETHEE I and II methods is used in order to model the multi criteria decision at hand.

### **3.4.1. Alternative/criteria matrix**

For comparison among different energy systems, various criteria could be considered. These criteria depend to a large degree on the situation and nature of the case, provided that the performance of energy systems varies with regard to the considered criterion. Sometimes these criteria are referred to as “sustainability indicators” meaning that these criteria identify the degree of sustainability of the energy systems (Afgan et al., 2000). Usually these criteria are classified into economic, environmental, technological, and social subgroups. They may be stated based on quantitative values or a given qualitative criteria. Investment cost, payback period, efficiency rate, and system emissions are stated based on quantitative units. Stakeholders’ judgmental values such as continuity and predictability of an energy technology, contribution to regional development, and contribution to employment opportunities creation can be shown on a scaled measure; for example, scale of 1-10, 1 being the worst and 10 being the best performance of an alternative (Cavallaro and Ciraolo, 2005).

For evaluation of energy systems six criteria are considered as follows:

- **Costs (economic factor, quantitative value):**

Considered costs are the present value (2005 base year) of the plants (including a 2.5 MW base-load system and a 10 MW peaking and backup natural gas system) at 10% discount rate. The cost of the plant includes land, building, major equipment, electrical and mechanical installations, soft costs (engineering, construction management and supervision), 7% provincial sales tax, contingency cost at 10%, maintenance cost, and operating cost (fuel and/or electricity cost and staff salary) over the 25-year service life of the system. Costs and benefits that are common and equal for different energy alternatives such as grid development, energy sales, and sale taxes are not considered (Compass Resource Management Ltd., 2006). For the sewer heat option, the extra costs of the sewage system include: redundant self cleaning screens, booster pumps, backwash pits, transfer pumps, electrical infrastructure, incremental building, stainless steel wetted interconnecting piping between treatment system and heat pump evaporator.

For the geothermal option, the cost of geothermal well includes wells, buried piping between wells and plant, pumps, and electrical infrastructure as required (Compass Resource Management Ltd., 2006; Trent Berry, 2006).

- **Total GHG emission of the system (global environmental impact, quantitative factor):**

This is the CO<sub>2</sub> equivalent emission of the 2.5MW base-load system and 10MW peaking and backup natural gas system. Biomass is considered to be GHG neutral. Reported number for biomass option also includes the GHG emissions associated with the road transportation of biomass from the nearest producing facility (275 Km) to the district heating system. For the electricity used in sewer heat and geothermal options heat pumps, GHG factor of 61.5 (tonnes GHG/GWh) is considered (Compass Resource Management Ltd., 2006).

- **Particulate Matter (PM) emission of the system (local environmental impact, quantitative factor):**

This includes particulate matter less than or equal to 2.5 µm in diameter. Number reported is the total PM<sub>2.5</sub> emission produced by the facility without an emission control system (Humphries et al., 2006).

- **Demand coverage risk (qualitative factor):**

This is a technical factor which shows the risks associated with each technology option in covering the estimated demand load. These risks include heat source variation or availability rate, experience with operation, and handling and future break downs of the system (Cavallaro and Ciruolo, 2005). For example, the developer group perception about the sewer heat pump option was that this system had very high demand coverage risk since such a system would be the first North American experience and no local experience was available. Seasonal as well as daily variations in sewage flow and temperature would add uncertainty to demand coverage. Moreover, the heat pump operation under low demand situations was problematic and required an additional

natural gas boiler to be installed for backup. The demand coverage risk is considered as a qualitative measure based on a five-point scale (1=very low, 5=very high).

- **Local source (qualitative factor):**

Whether or not the energy source is available within the community was considered as a binary criterion (0=locally not available, 1= locally available). The community representative group perceived geothermal heat and sewer heat options as local energy sources that would have secure supply over the service life of the facility and if not implemented, would be wasted.

- **Traffic load (qualitative factor):**

One of the community’s concerns raised particularly about the biomass option was about trucking in the biomass to the facility and taking out the remained ashes. The community representative group was concerned whether trucking of this fuel would have major traffic burden for the community. Therefore, this factor is considered as a binary value which is 1 for the biomass option and 0 for other options. Table 3-1 shows the alternatives/criteria matrix of the decision problem.

**Table 3-1. Alternatives/criteria matrix**

| Criteria             | Units                                | Alternatives |              |            |            |
|----------------------|--------------------------------------|--------------|--------------|------------|------------|
|                      |                                      | Natural gas  | Wood pellets | Sewer heat | Geothermal |
| Cost                 | 10 <sup>3</sup> CAD \$               | 16,875       | 14,688       | 19,041     | 23,521     |
| GHG emission         | Tonne/ yr                            | 7,875        | 2,564        | 3,635      | 4,081      |
| PM <sub>2.5</sub>    | Tonne/ yr                            | 0.14         | 2.40         | 0.04       | 0.04       |
| Demand coverage risk | Qualitative scale (1-5) <sup>a</sup> | 1            | 2            | 4          | 5          |
| Local source         | Binary value (0,1) <sup>b</sup>      | 0            | 0            | 1          | 1          |
| Traffic load         | Binary value (0,1) <sup>c</sup>      | 0            | 1            | 0          | 0          |

<sup>a</sup> Demand coverage risk due to insufficient experience with the technology, technical and operational risks, variation of heat source situation seasonally or in the long run. 1= very low, 2= low, 3= average, 4= high, 5= very high.

<sup>b</sup> Whether the heat source is available within the community’s boundaries. 0= it is not available, 1= it is available

<sup>c</sup> Whether shipment of fuel would have regular traffic load on the community (wood pellets issue). 0= no, 1= yes.

### **3.4.2. Decision making scenarios**

Two scenarios are examined to evaluate the final decision about the most suitable energy option of the considered district energy centre. The first scenario represents the actual decision process for selecting the energy option for the district heating system. In this scenario, criteria weights are extracted based on stakeholders' preferences obtained during the qualitative study phase. In the second scenario, as an ex-post attempt, we assume that the issues raised by concerned stakeholders about utilization of wood pellets at the district heating centre are addressed by the developer group. As a result of communication between stakeholders, information generated by the developer group about local issues of the wood pellets option was made available to all stakeholders. This scenario shows the effect of stakeholders' perceived performance of the wood pellets alternative with regard to important criteria, and consequently the final decision in a multi-criteria group decision making environment.

#### **3.4.2.1. Scenario I**

The developer group carried out the feasibility analysis of the district energy centre by studying the economics of different energy options available to the energy centre. The recommendation of the developer was to install a 2.5  $MW_{th}$  biomass combustion system for the base-load and a 10 MW natural gas boiler for peaking and backup. In the beginning of the implementation phase when the developer required regulatory permissions for the energy centre, the environmental and the community representative groups became more aware of the planned energy facility. At this stage, the idea of utilizing biomass in the energy centre was rejected by both the environmental and the community representative groups. The concerns of the community representative group were mainly regarding the negative effect of wood pellets utilization on the local air quality and traffic load due to biomass transportation to the facility. The environmental group's review of the energy options identified that the feasibility study carried out by the developer had not addressed such issues as particulate matter emissions from the biomass combustion system that was central for acquiring the air quality permission. Based on the

review of memorandums and comments received from the three stakeholder groups involved in the decision process, below ranking of decision criteria was inferred for each stakeholder:

- **Developer:**

$$Cost > Demand\ coverage\ risk > GHG\ emissions > PM\ emissions > Local\ source = Traffic\ load \quad 3-13$$

- **Environmental group:**

$$PM\ emissions > GHG\ emissions > Cost = Demand\ coverage\ risk = Local\ source = Traffic\ load \quad 3-14$$

- **Community representative group:**

$$PM\ emissions > Local\ source = Traffic\ load > Cost = Demand\ coverage\ risk = GHG\ emissions \quad 3-15$$

Table 3-2 summarizes the criteria weights considered for each stakeholder in scenario I using Equations 3-12. In this scenario, the number of criteria (n) is 6 and in a situation when criteria have equal importance, the average of weights is considered. For example, the criteria weights for the two criteria “Local source” and “Traffic load” considered for the developer based on the ranking expressed in Equation 3-12 would be the average of the criteria weights when Local source > Traffic load and Local source < Traffic load.

**Table 3-2: Criteria Weights considered in Scenario I**

| Stakeholders                                | Criteria |                      |              |                            |              |              |
|---|----------|----------------------|--------------|----------------------------|--------------|--------------|
|   | Cost     | Demand coverage risk | GHG emission | PM <sub>2.5</sub> emission | Local source | Traffic load |
| developer <sup>a</sup>                      | 0.41     | 0.24                 | 0.16         | 0.10                       | 0.045        | 0.045        |
| Environmental group <sup>b</sup>            | 0.0875   | 0.0875               | 0.26         | 0.41                       | 0.0875       | 0.0875       |
| Community representative group <sup>c</sup> | 0.06     | 0.06                 | 0.06         | 0.41                       | 0.21         | 0.21         |

<sup>a</sup> The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-13.

<sup>b</sup> The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-14.

<sup>c</sup> The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-13.

### 3.4.2.2. Scenario II

In this scenario, in an ex-post attempt, the major concerns of the environmental and community representative groups about the wood pellet burning facility, i.e. particulate

matter emissions from the biomass burning facility and traffic load due to biomass transportation are addressed.

In order to address concerns of environmental and community representative groups, the developer carried out additional analyses of the district energy centre, studying the particulate emissions from facility operation, GHG emissions of different energy options when transportation of wood pellets and emission factors for electricity used in heat pumps were included, and assessed the trucking requirement for wood fuel/ash hauling.

The issue of traffic burden of wood pellets fuel supply over the service life of the energy centre which was of great importance for the community representative group was evaluated based on a fuel supply/ ash disposal model (Trent Berry, 2006). The result of this analysis indicated that the supply of wood pellets could be secured through long term contract with a local wood pellets supplier. Moreover, the amount of wood pellets required for the biomass plant with a boiler of 2.5 MW would be about 5800 tonnes/ year. This volume of wood pellets could be scheduled for one truck of 40 tonnes capacity every 3 days. Also, ash disposal could be scheduled such that the same truck would be used for delivering the fuel and hauling the ashes (Trent Berry, 2006). This result was communicated to the authorities and the insignificant effect of biomass transportation to the energy centre on the local traffic was confirmed. Therefore, the effect of this criterion on the decision making in Scenario II is omitted.

In another study, the air quality assessment of the surrounding area of the district heating facility was carried out by the City (Humphries et al., 2006). Through meteorological modelling, it was estimated that through implementing the contribution of the biomass burning facility to the ambient air level of particulate matter emission would be, at the worst case, less than 2% of the local PM inventory (Humphries et al., 2006). The environmental group, which would provide inputs to the GVRD permit issuing process, however raised issues about the appropriateness of the study. The main issues were that the study used US EPA AP-42 emission factors in modelling the particulate emission levels and that the combustion and emission control systems were not specifically identified. US EPA AP-42 emission factors however do not recognize difference in the wood fuel properties and combustion systems and are averaged over

various measurements. In Scenario II it is assumed that the issue of PM emissions from facility is appropriately addressed and resolved. Therefore, its effect on the ex-post analysis is reflected in Scenario II by omitting the respective criteria from the decision matrix. Taking out the PM emissions and traffic load criteria from the criteria list, the criteria ranking by each stakeholder would change as follows:

- **Developer:**

$$Cost > Demand\ coverage\ risk > GHG\ emissions > Local\ source \quad 3-16$$

- **Environmental group:**

$$GHG\ emissions > Local\ source = Cost = Demand\ coverage\ risk \quad 3-17$$

- **Community representative:**

$$Local\ source = Cost = Demand\ coverage\ risk = GHG\ emissions \quad 3-18$$

The criteria weights shown in Table 3-3 are obtained from Equations 3-16 to 3-18 with  $n$  equals to 4 and equally important criteria are averaged as was done in the first scenario.

**Table 3-3: Criteria Weights considered in Scenario II**

| Stakeholders                                | Criteria |                      |              |              |
|---|----------|----------------------|--------------|--------------|
|   | Cost     | Demand coverage risk | GHG emission | Local source |
| Developer <sup>a</sup>                      | 0.52     | 0.27                 | 0.15         | 0.06         |
| Environmental group <sup>b</sup>            | 0.16     | 0.16                 | 0.52         | 0.16         |
| Community representative group <sup>c</sup> | 0.25     | 0.25                 | 0.25         | 0.25         |

<sup>a</sup>The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-16.

<sup>b</sup>The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-17.

<sup>c</sup>The criteria weights are obtained from Equation 3-12 and ranking stated in Equation 3-18.

### 3.5.Discussion

Table 3-4 shows the ranking of the alternatives obtained from the PROMETHEE II method for the three stakeholder groups in Scenario I and Scenario II.

**Table 3-4: Ranking of alternatives for each stakeholder based on PROMETHEE II**

|              |                            | Ranking                           |                                  |                                    |                                    |
|--------------|----------------------------|-----------------------------------|----------------------------------|------------------------------------|------------------------------------|
| Stakeholders |                            | 1                                 | 2                                | 3                                  | 4                                  |
| Scenario I   | <b>Developer</b>           | Wood pellets<br>( $\Phi = 0.47$ ) | Natural gas<br>( $\Phi = 0.21$ ) | Sewer heat<br>( $\Phi = -0.13$ )   | Geothermal<br>( $\Phi = -0.54$ )   |
|              | <b>Environmental group</b> | Sewer heat<br>( $\Phi = 0.35$ )   | Geothermal<br>( $\Phi = 0.14$ )  | Wood pellets<br>( $\Phi = -0.17$ ) | Natural gas<br>( $\Phi = -0.54$ )  |
|              | <b>Community group</b>     | Sewer heat<br>( $\Phi = 0.37$ )   | Geothermal<br>( $\Phi = 0.30$ )  | Natural gas<br>( $\Phi = -0.27$ )  | Wood pellets<br>( $\Phi = -0.40$ ) |
| Scenario II  | <b>Developer</b>           | Wood pellets<br>( $\Phi = 0.7$ )  | Natural gas<br>( $\Phi = 0.22$ ) | Sewer heat<br>( $\Phi = -0.22$ )   | Geothermal<br>( $\Phi = -0.71$ )   |
|              | <b>Environmental group</b> | Wood pellets<br>( $\Phi = 0.63$ ) | Sewer heat<br>( $\Phi = 0.12$ )  | Geothermal<br>( $\Phi = -0.31$ )   | Natural gas<br>( $\Phi = -0.45$ )  |
|              | <b>Community group</b>     | Wood pellets<br>( $\Phi = 0.68$ ) | Sewer heat<br>( $\Phi = -0.08$ ) | Natural gas<br>( $\Phi = -0.22$ )  | Geothermal<br>( $\Phi = -0.38$ )   |

The outcome of the PROMETHEE II method for Scenario I explicitly shows that stakeholders' interpretations regarding the best option are very diverse. The fact that wood pellets is the worst and second worst option for the community representative and environmental groups, respectively, stems from the concern of these groups about the effects of biomass burning facility on the local activities. Also, it can be seen that sewer heat recovery option is the best option for the environmental and community representative groups. Therefore, it can be expected that the sewer heat recovery option be chosen since the decision authority of these groups is higher than that of the developer. This result was similar to what was observed in reality.

In the ex-post analysis, the ranking of alternatives has changed (Scenario II), when the main points of conflict between the stakeholders about the wood pellets option were

addressed. In the decision making process where multiple decision makers with diverse backgrounds and viewpoints exist, if not impossible, it is difficult to reach at a single, globally agreed upon decision. When carrying out projects with public benefits or those that might be of public concern, the decision makers and stakeholders should be in communication with each other from the early stages of the project in order to discuss their objectives, values and/or concerns. MCDM methods can provide valuable basis for decision makers' discussions throughout this phase. It is important to involve or open a discourse with the public. Some important purposes of public involvement are: to inform the public, to reflect public values in the decisions, to consider the impacts that might be overlooked, and to provide 'due process' (Hobbs and Horn, 1997). Moreover, failure to involve the public in the decision process from the early stages may result in strong oppositions at the final stages of the decision making process from the public representative groups such as community associations, NGOs, and the media.

As the multi criteria decision making model presented here showed, in order to reach consensus about the energy source option of the district heating centre, all the legitimate stakeholders should be identified accurately and their perceptions, viewpoints, and concerns should be included and addressed in the feasibility studies of potential district energy systems. The accurate data and information produced during the feasibility study of the system should then be conveyed to stakeholders properly (ex-post study in scenario II).

Moreover, analysis of decision making process about the heat source option of the considered district heating centre showed that general perception about particulate matter emission of wood pellets burning and upstream emissions and environmental impacts of biomass acquisition, processing, and transportation are major selection issues for biomass based district heating centres in the Vancouver area.

### **3.6. Conclusions**

In this chapter, four energy options of natural gas, wood pellets, sewer heat recovery, and geothermal exchange to provide the base-load heat demand of a district energy system in Vancouver (BC) were considered. The analysis of the decision making process

for selection of the heat source option was carried out in order to identify the key stakeholder groups', decision making criteria, and consequently the major issues in selecting wood pellets as an energy source in district heating centres.

The PROMETHEE II method was used to rank the alternatives against six criteria of cost, GHG emissions, PM emissions, demand coverage risk, traffic load, and local source. Two scenarios were investigated to indicate how the consensus between the stakeholder groups involved in the district energy project can be reached through good communication during the feasibility study and decision making process. The first scenario represented the real case of decision making where there was no communication between stakeholders. This fact was reflected in the analysis by the decision makers' preferences and ranking of criteria by them. Based on the ranking, criteria weights were assigned using the Expected Value method. The PROMETHEE results conformed to the decision made in the real case. Despite advantages of utilizing biomass in the considered district energy system, such as low capital cost, advanced burning technology, low demand coverage risk, and GHG neutrality, it was not chosen as the heat source option since the concerns of local groups were not addressed properly during the feasibility study phase. The sewer heat option was selected because of the higher decision authority of the opposing groups and the fact that the information about biomass option was not communicated to other stakeholders well. In the second scenario, it is assumed that communication was facilitated among the stakeholders and concerns of the stakeholders regarding particulate matter emissions and traffic load burden were addressed during the decision process. Therefore, the traffic load and PM emission criteria were omitted from the analysis. Based on the decision makers' ranking of criteria and applying the Expected Value method, the importance of criteria was derived. The PROMETHEE results showed a general agreement among stakeholders. The top ranked alternative in this scenario for all stakeholders were the same indicating that concerns about local impacts of wood pellets option is a pivotal criterion in selection of this heat source option and also that transparency and communication would help reaching consensus. In this study it is concluded that besides the technical and economic factors, environmental and social acceptability were among the decision making criteria for selection of heat source option for district heating systems in Vancouver when wood pellets is among options. The main

issues regarding the selection of wood pellets were related to the environmental impacts of wood pellet production and transportation to the facility and the particulate matter emissions from combustion of wood pellets in the district heating centre.

## **Chapter 4. Particulate matter emissions from combustion of wood in district heating applications\***

### **4.1. Synopsis**

The perception of stakeholders regarding particulate emission levels from combustion of wood pellets at the district heating centre is deemed a pivotal factor in acceptance of this energy source. The project developer used the US EPA AP-42 factors in order to calculate emission levels from combustion of wood pellets in district heating applications. However, these factors do not account for differences in wood fuel properties and are average of several measurements on combustion systems with various size ranges. Therefore, the use of these factors for this specific case is unsatisfactory.

The primary aim of this chapter is to provide measured ranges of particulate emissions from the literature on wood-based heat producing systems that can typically be used for district heating applications. The secondary objective is to provide insight into factors influencing particulate matter emission levels from typical size district heating systems (from ~500 kW to ~10 MW) utilizing wood biomass. Special attention is paid to the effects that combustion condition and natural variations of wood composition would have on the particulate matter emission levels from wood combustion.

### **4.2. Introduction**

Recent efforts towards reducing greenhouse gas emissions have led many countries to utilize renewable energy sources for heat and power generation purposes. Among renewable sources, wood biomass is considered as a greenhouse gas neutral energy source; therefore governments have been implementing policy measures to increase the share of wood biomass in their countries' primary energy source basket.

In countries where abundant sources of biomass are available, producing all or part of energy requirements of communities from biomass is now a well established concept.

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\* A version of this chapter has been submitted for publication. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, T., Melin, S., Particulate matter emissions from combustion of wood in district heating applications.

Sweden is a good example among countries with established market for utilizing various forms of wood biomass in community heat and power applications (Mahapatra et al., 2007). Despite its wide application, there are concerns about potential negative human health impacts of certain pollutants concentration in the air from combustion of wood fuel for energy generation in populated areas.

Scientific evidences indicate that human exposure to airborne particulate matter emissions can have far severe health implications than many other airborne pollutants (Vedal, 1997). Samet et al. (2000) found that the rate of death was correlated to the level of PM<sub>10</sub> concentration in the ambient air. Pope et al. (Pope III et al., 2002) concluded that long-term exposure to fine particulate matter from combustion would have approximately a 6% and 8% increased risk of cardiopulmonary and lung cancer mortality, respectively. Exposure to ultra-fine particulates (0.01 to 2.5 µm - PM<sub>2.5</sub>) could increase the risk of severe respiratory disease (Peters et al., 1997). Also, the chemical composition of particles influences the severity and type of health effects.

Uncontrolled wood combustion will emit a variety of air pollutants to the atmosphere (Boubel et al., 1994). Van Loo and Koppejan (2008) list primary emissions of wood combustion as: carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), methane (CH<sub>4</sub>), non methane volatile organic compounds (NMVOC), nitrogen oxides (NO<sub>x</sub>) and nitrous oxide (N<sub>2</sub>O), ammonia (NH<sub>3</sub>), sulfur oxides (SO<sub>x</sub>), particulate matters (PM), trace elements of heavy metals, dioxins and furans-polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Concerns about wood combustion for community energy generation in a populated area are mostly related to particulates found in the flue gas (Harrison and Yin, 2000). Among the toxic chemical compounds that can be found in the combustion of material with chlorine content are dioxins and furans. Dioxins and furans are among ultra-fine particles (below 1 µm in diameter) emitted to the atmosphere from wood combustion. Dioxins and furans in air, water, soil and food cause negative health effects, such as carcinogenicity, immunotoxicity, and disturbance of lipid metabolism in humans (Flesch-Janys et al., 1995). It has been consistently observed that human exposure to dioxins and furans increases the mortality rate in all cancer types including rectal and lung cancers (Bertazzi et al., 2001). Negative effects on endocrine

and reproductive system are among the most sensitive effects of dioxins and furans (Kogevinas, 2001). Trace elements of metals, such as sodium, potassium, cadmium, lead, mercury, and arsenic that can be found in the wood combustion flue gas particles in very small amounts have toxic effects on human (Harrison and Yin, 2000). Therefore, monitoring and controlling both concentration and composition of particulate matters in the air should be of the highest importance for municipal authorities (Harrison and Yin, 2000).

Usually each regional district has regulatory emission limits in place for point source emitters in order to maintain the desirable local air quality. In 2008, Metro Vancouver introduced air contaminant discharge bylaw within the region. The regulations divided the boiler and heat producing systems into three categories of small (<3 MW), medium (3-50 MW) and larger than 50 MW systems. This regulation, sets the maximum total filterable particulate matter emission at  $18 \text{ mg/m}^3$  (at  $20^\circ\text{C}$ ,  $101.325 \text{ kPa}$ , dry gas, and  $8\% \text{ O}_2$ )<sup>3</sup>. For rural applications, the maximum particulate matter is set at  $30 \text{ mg/m}^3$ . An urban facility is defined as a boiler or heater operating within 500 m of more than 20 residential or business premises, schools, hospitals, and such a like. The regulation sets the limits for nitrogen oxides at  $120 \text{ mg/m}^3$ , and carbon monoxide at  $120 \text{ mg/m}^3$  for new or modified systems and  $200 \text{ mg/m}^3$  for the existing boilers (Metro Vancouver, 2008). This regulation defines wood products as wood pellets, hog fuel, mill ends, wood chips, bark, shavings or sawdust and industrial residue of wood that has not been treated with glue, paint and preservative, or do not contain foreign substances harmful to humans, animals or plants when combusted (e.g. salt laden wood). Composition of particulates is highly important when considering human toxicity effects of airborne pollutants (Oberdorster et al., 1995). Most regulations impose limits on mass concentration measures of particulate emissions regardless of their specific chemical composition.

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<sup>3</sup> Mass concentration of particulate emissions in the flue gas are stated in  $\text{mg/m}^3$  with the reference condition (temperature and pressure). The  $\text{mg/Nm}^3$  unit represents mass concentration under normal gas condition (*N* stands for conditions  $0^\circ\text{C}$ ,  $101.325 \text{ kPa}$ ).

### 4.3. Particulate matters from wood combustion

Primary particulate emissions from wood combustion are from two main sources: 1) particulates from complete combustion including inorganic material in the fly ash, and 2) particulates from incomplete combustion including soot, condensable organic particles (tar), and char (Johansson et al., 2003).

It has been reportedly shown that particulate mass concentration in the flue gas of complete wood combustion has two distribution peaks (coarse peak and fine peak) (Boman et al., 2004; Hasler and Nussbaumer, 1998; Obernberger et al., 2001; Wiinikka, 2005). Sub-micron flying ash particles ( $<0.5\mu\text{m}$ ) are produced from vaporization of easily volatilized ash components (S, Cl, Na, K) and the heavy metal zinc (Wiinikka and Gebart, 2004). Coarse particles are formed from residual flying ash particles ejected mechanically from the fuel bed and are carried by the flue gas upwards (Wiinikka and Gebart, 2004) or intractable ash compounds of Ca, Mg, Si (if present) (Strand et al., 2002).

Incomplete combustion is a result of unfavorable combustion conditions such as inadequate mixing of air and fuel in the combustion chamber, low combustion temperatures, or short residence times (Van Loo and Koppejan, 2008). Under incomplete combustion, submicron organic particles (soot  $<0.5\mu\text{m}$ ) can be produced (Wiinikka and Gebart, 2004). Boman et al. (2004) tested 6 different pellet fuel types in three different commercial pellet burners (10-15 kW) and observed that ultra-fine particles ( $<1\mu\text{m}$ ) constitute  $89.5\% \pm 7.4\%$  of total PM emissions from the systems, 28-92% of which were products of incomplete combustion. Advanced industrial wood combustion technologies which are available today can achieve more complete burnout of wood fuel and produce less incomplete combustion emissions compared to small scale and old type burners through maintaining desirable combustion condition (Van Loo and Koppejan, 2008). Wood fuel properties (Obernberger and Thek, 2004) and combustion technology (Johansson et al., 2004) affect composition as well as amount of particulate matter emissions leaving the combustion chamber.

### **4.3.1. Wood properties**

The European Standardization Committee for solid biofuels (CEN/TC 335) defines the quality of wood biomass by its physical properties and chemical content. Physical properties of wood biomass include moisture content, density, calorific value, ash content, and volatile matter content. The elemental content of wood biomass consists of C, H, N, S and Cl, water soluble Cl, Na and K content, major elements (Al, Si, K, Na, Ca, Mg, Fe, P and Ti) content, and minor elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V and Zn) (Alakangas et al., 2006). These chemical and physical properties (referred to as wood fuel quality), either directly or through affecting the combustion condition, affect the content and/or amount of combustion emissions (Van Loo and Koppejan, 2008).

#### **4.3.1.1. Moisture content**

Moisture content of wood fuel influences the net calorific value of the fuel, combustion temperature and combustion efficiency (Oberberger and Thek, 2004). The first step in biomass combustion starts with the drying phase, in which water content of the fuel vaporizes. The amount of energy required in this phase is lower for fuels with low moisture content compared to that for fuels with high moisture content (Nussbaumer, 2003), thus the combustion temperature for low moisture content fuels would be higher leading to a complete burnout. Moisture content of wood pellets is in the range of 4-10% (wb), while the moisture content of undried green wood is as high as 50% (Oberberger, 1998). It is very difficult to maintain a continuous combustion for wood fuel with more than 60% moisture content since the energy required to vaporize the moisture in wood exceeds the energy produced by the dry part of the wood (Van Loo and Koppejan, 2008).

#### **4.3.1.2. Ash content**

Ash content (or inorganic materials) and insoluble compounds act as a heat sink in the same way as moisture and results in lower combustion efficiency (Demirbas, 2005). Apart from decreased combustion efficiency and higher chance of forming coarse flying ashes in the flue gas, using ash rich wood fuels such as bark and solid forest residues in

wood burners cause operational problems such as sintering and formation of hard deposits in the furnaces and boilers (Ohman et al., 2004).

High ash content in the wood fuel stems from natural variations in raw material, existence of mineral impurities, chemical/biological additives (Oberberger and Thek, 2004), and/or microbial growth during storage (Lehtikangas, 2001). European standard for solid biofuels considers contamination with soil and sand, high content of bark, use of inorganic additives, chemical treatments such as paint, and preservation as general sources of higher ash content in pellets (Alakangas et al., 2006).

Chemical content of Cl, S, major elements (Al, Si, K, Na, Ca, Mg, Fe, P and Ti) content, and minor elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V and Zn) in the wood fuel form the ash components of wood fuels which directly affect aerosol and fly ash formation during wood fuel combustion (Oberberger et al., 2006).

#### **4.3.1.3. Chlorine content**

Chlorine content plays an important role in forming alkali metal chlorides, releasing the ash forming elements to the gas phase which leads to fine particulate formation (Sippula et al., 2008). Chlorine compounds are among dominant chemical compositions in the aerosol range of particulate emissions from wood combusting district heating systems (Johansson et al., 2003; Oberberger et al., 2001; Strand et al., 2002).

Chlorine content of fuel translates to the possibility of dioxin and furan formation during combustion (Huang and Buekens, 1995). The dioxin and furan emissions from wood combustion are due to the presence of phenols and lignin or particulate carbon and chlorine (Chagger et al., 1998). Combustion of uncoated natural wood produces significantly lower amounts of dioxin and furan emission than other fuel types such as straw, coal and sewage sludge (Salthammer et al., 1995); this is due to very low natural content of chlorine element in the white wood (Schatowitz et al., 1994). On the other hand, during wood combustion, dioxin and furan compounds are more often bound to the surface and carried away by fly ash particles. This portion of dioxin and furan emissions in the flue gas can effectively be reduced by primary and secondary emission control measures such as utilizing high quality wood fuel, optimal combustion condition, and fly

ash precipitation at low temperatures (<200°C) (Lind et al., 2006). Lavric et al. (2004) reviewed studies which aimed at measuring and characterizing dioxin emissions from wood combustion. They concluded that combustion condition (combustion technology, operating condition, load condition) and fuel properties (size distribution, shape, moisture and ash contents, and ash melting behavior) are the most influential parameters on the level of dioxin emissions. Table 4-1 shows the reported dioxin levels from wood combustion technologies that are in the size ranges suitable for district energy applications (from ~500 kW to ~10 MW).

**Table 4-1: Dioxin levels from wood fuel combustion in small and medium sized burners  
adopted from: (Lavric et al., 2004)**

| Combustor type/ application            | Wood fuel type                      | Gas cleaning system          | Dioxin emission,<br><i>ng I – TEQ/dscm</i><br>at 11% O <sub>2</sub> |
|--|-------------------------------------|------------------------------|---|
| Moving grate<br>(2 MW)                 | Bark chips                          | N/A                          | 0.019   |
| Moving grate<br>(16 MW)                | Bark chips                          | N/A                          | 0.006   |
| Wood dust burner<br>(9.6 MW)           | Pine chips                          | N/A                          | 0.004-0.006   |
| Grate burner<br>(11 MW)                | Wood chips                          | ESP                          | 0.007   |
| Grate burner<br>(1 MW)                 | Wood chips                          | Cyclone, bag filter          | 0.050   |
| Grate burner<br>(0.6 MW)               | Wood chips                          | Cyclone, ESP                 | 0.039   |
| Moving grate<br>(13.8 MW)              | Pine wood                           | Multi- cyclone               | 0.0783  |
| Moving grate<br>(6.3 MW)               | Wood chips                          | N/A                          | 0.0027  |
| Grate firing<br>(850 kW)               | Waste wood chips<br>from demolition | Cyclone/ fabric filter       | 2.7   |
| Grate firing<br>(1.8 MW)               | Waste wood chips<br>from demolition | Cyclone/ ESP                 | 9.57  |
| Moving grate<br>(850 kW)               | Urban waste wood                    | Cyclone/ cloth filter (Ca/C) | 2.04  |
| Bubbling fluidized bed<br>(4 MW)       | Wood chips/ 15-<br>45% RDF          | ESP                          | <0.1  |
| Fluidized bed<br>(12 MW)               | Urban waste wood                    | N/A                          | 0.1   |
| Circulating fluidized bed<br>(17.5 MW) | Urban waste wood                    | Cyclone/ ESP                 | 0.71-0.73   |

Uncontaminated natural wood combustion in small and medium sized modern plants with flue gas cleaning systems, under good burnout condition, will produce dioxin emission levels well below the health risk limit of  $0.1 \text{ ng I-TEQ/m}^3$ <sup>4</sup> (Lavric et al., 2004).

#### **4.3.1.4. Sulphur content**

Sulphur content of wood fuel, reacts with alkali metal chlorides and hydroxides during the combustion process through sulphation reactions. The nucleation and condensation temperatures of alkali metal sulphates are higher than that of chlorides so less volatile sulphates are formed (Sippula et al., 2008). It has been reported that sulphur decreases the release of chlorine, therefore induced fine mode particles in biomass combustion (Lind et al., 2006; Miller et al., 2003). Nonetheless, S content negatively affects the release of Cl and formation of corrosive compounds such as  $\text{FeCl}_2$  or  $\text{ZnCl}_2$  at lower temperatures during wood combustion (Obernberger et al., 2006). Potassium sulphate is generated in small amounts during wood combustion and has been observed as a dominant compound in the aerosol range fly-ash of wood combustion (Johansson et al., 2003; Lillieblad et al., 2004; Valmari et al., 1998).

#### **4.3.1.5. Major and minor elements**

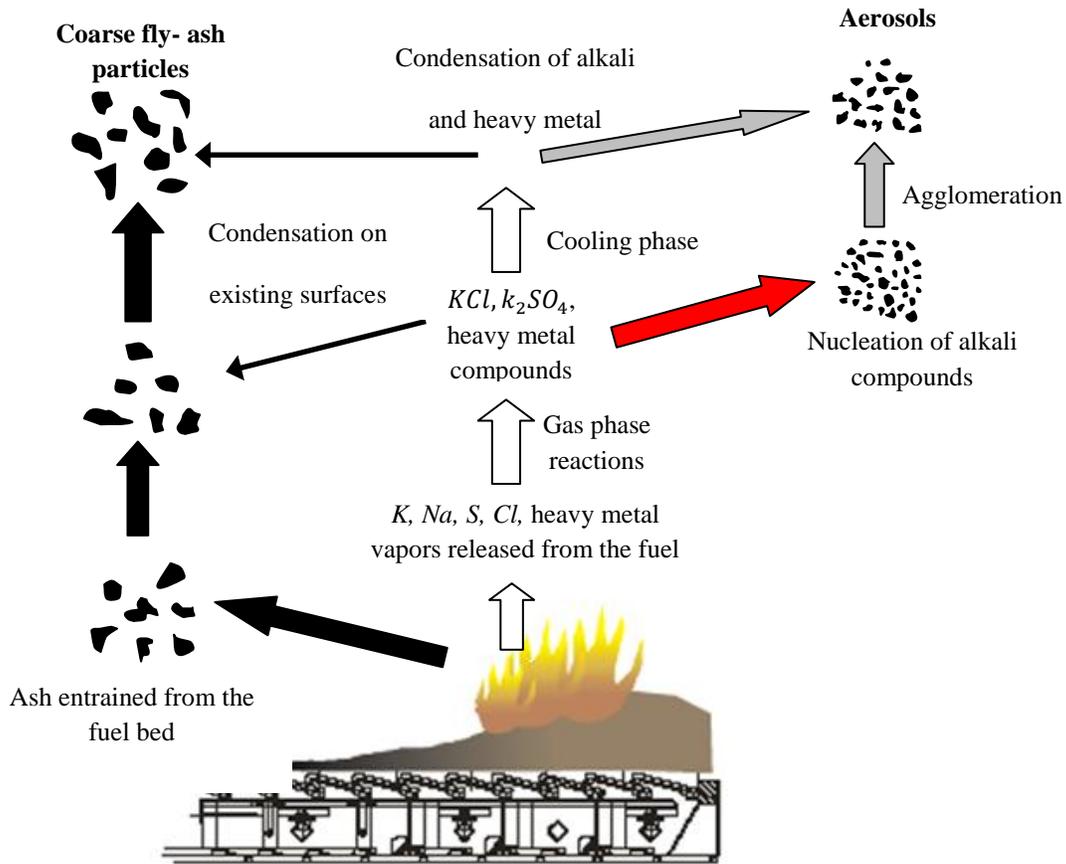
During the devolatilization period of biomass combustion when volatile contents of biomass vaporize, inorganic elements of biomass including Na, K, Mg, Al, and Ca are retained within the biomass char. After the devolatilization process, vaporization of monovalent metals of Na and K takes place, while divalent and trivalent metals of Mg, Al, and Ca are more highly retained in biomass chars (Wornat et al., 1995). The main ash-forming elements found in the fly-ash of wood combustion (besides Cl and S) include K, Na, Zn, Pb, Cd, Cr, Mg (Obernberger et al., 2006). Figure 4–1 shows the general mechanisms leading to coarse and fine mode formation of particle emissions in a

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<sup>4</sup> *I-TEQ*: International Toxicity Equivalent factor initially set by North Atlantic Treaty Organization (NATO) in 1989 expresses the toxicity level of a mixture of toxics as a single number. *I-TEQ* equals the level of toxicity of the mixture of toxics to that of 2, 3, 7, 8- TCDD (tetrachlorinated dibenzo- p- dioxin) which is the reference compound.

fixed-bed combustor from major and minor ash-forming elements present in untreated wood.

**Figure 4–1: Aerosol formation during fixed bed combustion of untreated wood**  
 source: (Obernberger et al., 2001)



Compositional analysis of the flue gas of district heating systems operating on wood fuels has shown that refractory species such as Ca and Mg as well as small amounts of Si, P, Fe and Mn (from low quality wood fuels such as forest residues) are dominant in the coarse mode (Lillieblad et al., 2004; Obernberger et al., 2001; Strand et al., 2002; Valmari et al., 1998). Vaporized compounds of alkali metals (K and Na) are dominantly present in the fine mode (Johansson et al., 2003; Lillieblad et al., 2001; Lillieblad et al., 2004; Valmari et al., 1998). Smaller amounts of these species observed in the coarse mode of wood burning district heating systems flue gas (Obernberger et al., 2001) are resulted from bounding of these volatile compounds (Obernberger et al., 2006). Heavy metal traces of Cd, Zn, Cr, (Obernberger et al., 2001; Raili and Martti, 1996; Strand et al.,

2002; Valmari et al., 1998; Wierzbicka et al., 2005) as well as Pb, Hg, As, Cu (Raili and Martti, 1996) are dominantly present in the vaporized form and the aerosol mode (Obernberger et al., 2006) of wood combustion flue gas from district heating systems.

Table 4-2 shows key physical properties and chemical composition of uncontaminated, natural, solid softwood fuels.

**Table 4-2: Physical and chemical properties of uncontaminated, natural, solid softwood fuels adopted from: (Obernberger, 1998; Obernberger and Thek, 2004; Obernberger et al., 2006)**

| Parameter    | Unit                         | Wood pellet | Wood chips | Sawdust | Bark | logging residues |
|--------------|------------------------------|-------------|------------|---------|------|------------------|
| Moisture     | wt% (w.b. *)                 | 7           | 50         | 50      | 50   | 50               |
| Ash          | wt% (d.b. *)                 | < 0.5       | 0.3        | 0.3     | 4    | 2                |
| Bulk density | kg/<br>m <sup>3</sup> (w.b.) | 591         | 350        | 240     | 320  | <350             |
| Cl           | wt% (daf)                    | 0.005       | 0.01       | 0.01    | 0.02 | 0.01             |
| S            | wt% (daf)                    | 0.027       | 0.02       | 0.02    | 0.1  | 0.04             |
| K            | mg/kg (d.b.)                 | 493         | 400        | 400     | 2000 | 2000             |
| Na           | mg/kg (d.b.)                 | 20          | 20         | 20      | 300  | 200              |
| Cd           | mg/kg (d.b.)                 | 0.14        | 0.1        | 0.1     | 0.5  | 0.2              |
| Zn           | mg/kg (d.b.)                 | 13.2        | 10         | 10      | 100  | <100             |
| Pb           | mg/kg (d.b.)                 | 0.43        | 2          | 2       | 4    | 3                |
| Cr           | mg/kg (d.b.)                 | 0.6         | 1          | 1       | 5    | <5               |
| Cu           | mg/kg (d.b.)                 | 1.1         | 2          | 2       | 5    | <5               |
| Ca           | mg/kg (d.b.)                 | 900         | 900        | 900     | 5000 | 5000             |
| Mg           | mg/kg (d.b.)                 | 150         | 150        | 150     | 1000 | 800              |
| Mn           | mg/kg (d.b.)                 | 147         | 147        | 147     | 500  | 251              |
| Hg           | mg/kg (d.b.)                 | 0.02        | 0.02       | 0.02    | 0.05 | 0.03             |
| As           | mg/kg (d.b.)                 | <0.1        | <0.1       | <0.1    | 1    | 0.3              |
| P            | mg/kg (d.b.)                 | 60          | 60         | 60      | 400  | 500              |

Explanation: Wood pellet values are from direct measurement study (Obernberger and Thek, 2004) when different than stem wood value estimates.

\* w.b.: Wet basis, d.b.: dry basis

As it can be seen in the table, wood fuels obtained from softwood stem (wood pellet, wood chips and sawdust) contain very low amounts of alkali metals and dioxin, furan, and fine particle forming elements; while these amounts are much higher in other parts of the tree such as bark and mixed logging residues (Obernberger et al., 2006). Most importantly the natural content of Cl in the softwood stem is well below the guiding concentration of 0.1 wt% (d.b.) associated with the dioxin and furans emissions. In processed wood, higher Cl, S, K, and Na content can also be an indication of organic or inorganic additives (such as insecticides, adhesives, glues, lacquer, dyestuff, or wood preservatives) in the raw material (Obernberger and Thek, 2004), higher content of bark

than specified, and/or contamination during storage/ transportation by salt water, road salting, and preservation chemicals (Alakangas et al., 2006). Higher content of Si or Na in the wood fuels than wood natural content can be related to mineral impurities such as sand or glass during handling and processing (Oberberger and Thek, 2004).

#### **4.3.2. Biomass combustion systems**

Different combustion technologies without utilizing high efficiency flue gas particulate abatement equipment yield various amounts of particulate matter emissions ranging between 60 and 2100 mg/Nm<sup>3</sup> (Johansson et al., 2003). With the introduction of improved biomass combustors in the past two decades, higher combustion efficiencies and lower emissions are now observed from these systems compared to old-type wood burning boilers (Johansson et al., 2004).

Biomass combustion systems are available in sizes ranging from a few kW up to more than 100 MW. Below 100 kW<sub>th</sub> systems are usually referred to as small-scaled systems (Oberberger et al., 2006). Medium and large scaled combustion technologies used to produce heat from biomass include: 1) grate stoker burners, 2) fluidized bed combustors, 3) suspension burners, and 4) two-stage gasification-combustion systems (Bain et al., 1998; Demirbas, 2005; Oberberger, 1998; Oberberger et al., 2006; Van Loo and Koppejan, 2008).

In grate stoker burners, a stoker spreads wood biomass on a stationary sloping, vibrating, or moving grate on which combustion takes place (Bain et al., 1998). In these burners, the grate is responsible for lengthwise transport of fuel and distribution of the primary air. Grate burners with moving grates (traveling, reciprocating, and vibrating) have more control over burning process, more complete burnout, less organic emissions, and higher overall efficiencies compared to those with stationary grates (Yin et al., 2008). Among moving grates, vibrating grates (Yang et al., 2007) have less moving parts compared to traveling (Narayanan and Natarajan, 2007) and reciprocating (Yang et al., 2007) grates, therefore their operating and maintenance costs are lower than those of traveling and reciprocating burners.

Fluidized bed boilers are complex and capital intensive technologies (Energy and Environmental Analysis Inc., an ICF International Company, and Eastern Research Group Inc., 2007) that are usually attractive for plants over 20 MW<sub>th</sub> capacity (Van Loo and Koppejan, 2008). In fluidized bed combustion systems, biomass is introduced to a suspension bed of hot and inert granular material (fluidized bed) (Van Loo and Koppejan, 2008). The main types of fluidized bed are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) (Bain et al., 1998). Ultra-fine particle emissions of tar and aerosols sourcing from incomplete combustion are negligible in fluidized bed combustors as a result of more homogeneous temperature in the combustion bed. However, the amount of macro particles of fly ash, dust and unburned carbon entrained in the flue gas from the combustion bed is high (Valmari et al., 1998). Circulating fluidized bed captures the unburnt carbon in the flue gas and returns it to the combustion bed for complete burnout. However, the level of macro particulate emissions from combustion systems fired with low-ash biomass fuels is expected to be negligible (Permchart and Kouprianov, 2004).

In suspension burners, fine particles of pulverized wood are pneumatically injected into the furnace (Van Loo and Koppejan, 2008) where combustion takes place. In suspension burners three steps under controlled staged-air circumstances can be recognized: 1) devolatilization to char and volatiles, 2) combustion of the volatiles, and 3) combustion of the char (Williams et al., 2001). Suspension burners may be designed to handle different fuel types in various modes of solid, liquid, or gas. Examples include co-firing of biomass with coal in pulverized burners (Sami et al., 2001) or co-combustion of biomass in natural gas fired furnaces (Casaca and Costa, 2003). Controlled range of wood powder particle size (<2 mm) (Spliethoff and Hein, 1998) and low moisture content of fuel (less than 15%) (Bain et al., 1998) are two key parameters leading to complete burnout of fuel and therefore low emissions in the suspension burners. Direct burning of pulverized biomass in suspension burners has limited applications mainly due to the extensive fuel preparation requirement (Bain et al., 1998; Werther et al., 2000). Particulates in the fly ash of biomass suspension firing is considerably higher than grate and fluidized burning methods since in this method, major parts of the particulates will end up in the fly ash. There are also problems associated with higher amount of NO<sub>x</sub> emissions from this type of biomass combustion because of difficulties in staging of

the combustion process in such burners (Tillman, 1987). Extensive literature on application of pulverized burners for co-firing of coal with biomass is available (Hein and Bemtgen, 1998; Williams et al., 2001), though studies aiming at characterization and direct measurement of particulate emissions from biomass burning in such burners could not be found.

The two-stage gasification-combustion is based on the gasification reaction. At first, under partial oxidation condition at high temperatures, a combustible gas mixture called syngas would be generated from biomass. This gas mixture which has relatively low calorific value can be burnt directly in an oxidizer attached to a boiler for hot water or steam generation (McKendry, 2002). Direct combustion of the produced syngas from gasification process in an oxidizer or a boiler for heat generation purposes is a rare application of this technology (Bridgwater, 2001). Two-stage combustion technologies have been commonly practiced in the industry to control CO and NO<sub>x</sub> emissions. The syngas in this case is not a product but an intermediate in the combustor. Syngas produced from biomass gasification contains high amounts of tar, char, and other particulates which are a major issue for direct utilization of this gas in turbines and engines (Devi et al., 2003; Tomishige et al., 2004). Published material reporting the amount of particulates and emissions in the flue gas after direct combustion of treated/untreated syngas is not available.

### **4.3.3. Flue gas cleaning systems**

In order to reduce emissions of particulate matters from biomass combustion usually flue gas cleaning equipment is used. Major flue gas cleaning systems applied in wood combustion applications include: 1) cyclones, 2) electrostatic precipitators, and 3) baghouses (Van Loo and Koppejan, 2008).

#### **4.3.3.1. Cyclones**

Cyclones use centrifugal forces to separate dust and solid particles from gas and are widely used in the industry (Van Loo and Koppejan, 2008). Separation efficiency of cyclones is higher for coarse particles. Finer particles (<10 $\mu$ m) exit at the top of the cyclone with the flue gas (Shin et al., 2005). Separation efficiency of cyclones is around

85% for  $PM_{10}$  and decreases to below 20% for particulates with less than  $5\mu m$  aerodynamic diameter (Jiao and Zheng, 2007). There has been extensive effort to increase separation efficiency of cyclones (Qian et al., 2006), yet, cyclone separators are most often used for the primary dust collection purposes (Shanthakumar et al., 2008) downstream of which a more efficient emission control system like an electrostatic precipitator or a baghouse is used.

#### **4.3.3.2. Electrostatic precipitators**

Electrostatic precipitators (ESP) electrically charge the suspended particles in the flue gas and then attract them to an electrode plate from where they can be removed (Van Loo and Koppejan, 2008).

The overall collection efficiency of ESP systems in terms of mass volume ( $mg/Nm^3$ ) is more than 99%. Nonetheless, overall collection efficiency of ESPs in terms of particle numbers (number of particles/ $Nm^3$ ) might be as low as 50% since sub-micron particles are very likely to escape the electrical fields (Chang, 2003). Improved ESP systems have been reported to clean the ultra-fine particles from combustion flue gas with efficiencies in the range of 95%. An improvement on ESP of a pulverized coal burning facility increased the collection efficiency of unburnt carbon particles or fly ash in the diameter range of  $0.06$  to  $12\mu m$  to 98% (Watanabe et al., 1995). Yoo et al. (1997) tested a two-stage parallel-plate ESP in the laboratory on very fine NaCl, fly ash and aerosol particles between  $0.03$  and  $0.2\mu m$  diameter. The collection efficiency of this system was reported at 93-98%. Strand et al. (Strand et al., 2002) observed a collection efficiency of 82.7% for an ESP system on sub-micron particles ( $<0.8\mu m$ ). The same measurements for particles between  $0.8$ - $6\mu m$  showed that ESP collection efficiency was 95.6% for course particles. Lind et al. (2003) reported a total collection efficiency of 99.2- 99.8% for an ESP installed after a 66 MW biomass-fueled bubbling fluidized bed. For particles in the size range of  $0.1$ -  $2\mu m$ , the collection efficiency of the ESP was 96-97%.

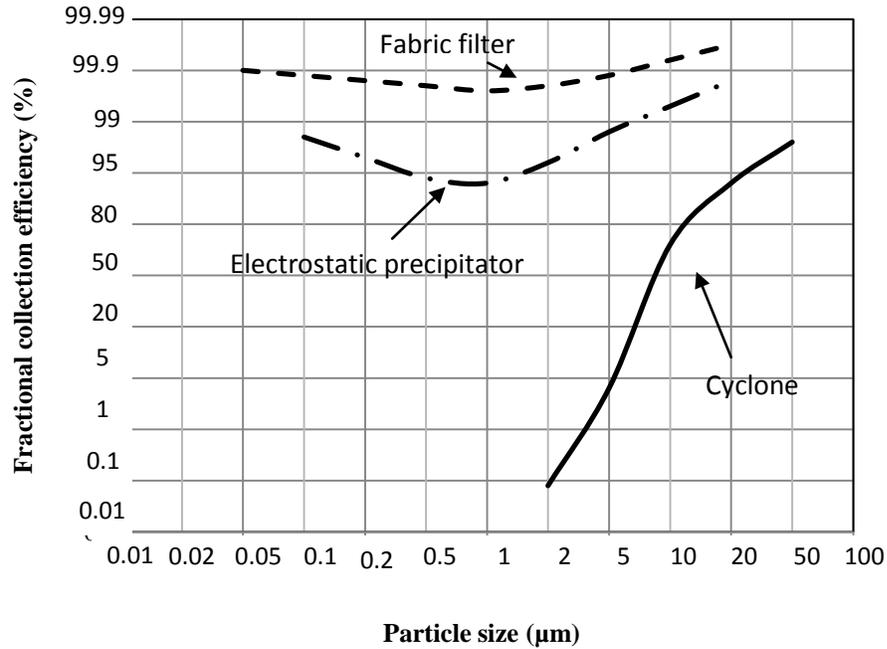
#### **4.3.3.3. Baghouses**

In baghouse systems, the suspended particulates in the combustion flue gas are collected on the surface of a sieving textile media (fabric filter) (Van Loo and Koppejan,

2008). Baghouses are economical and effective systems that are widely used for industrial emission control (Sutherland, 2008). A baghouse, if designed properly, is able to remove multiple pollutants such as particles, heavy metals, dioxins and furans from the flue gas (Tejima et al., 1996). Ergüdenler et al. (1997) observed dust and particle collection efficiencies well above 99.5% from baghouses with high temperature resistant ceramic filters applied to flue gas stream generated in the laboratory. Also, trace element collection efficiency of a baghouse on a pulverized coal boiler was reported over 95% for particles as small as 0.08  $\mu\text{m}$  (Shendrikar et al., 1983). Collection efficiency of baghouse filter systems depends to a great extent on key design parameters such as the choice of filter fabric and air-to-cloth ratio (Cora and Hung, 2002). An overview of baghouse cleaning systems is given in (Cora and Hung, 2002).

Figure 4–2 shows the collection efficiency range of conventional gas cleaning systems. As it can be seen from this figure, fabric filters and electrostatic precipitators have high collection efficiency well above 95% at sub-micron particle ranges. The reason for the “U” shaped collection efficiency curve of ESP systems has been explained by the decreased charge of smaller size particles until this effect is offset by the increasing mobility property of ultra- small particles (due to reduced drag force) (Zhuang et al., 2000). More detailed review of cleaning technologies, especially ESP systems that have vast applications for wood combustion flue gas cleaning can be found in (Jaworek et al., 2007).

**Figure 4–2: Collection efficiency of conventional gas cleaning technologies adopted from: (Hasler and Nussbaumer, 1999)**



#### 4.4. Discussion

In order to estimate particulate emissions from wood combustion in district heating systems, US EPA AP-42 emission factors for particulate emissions from wood residue combustion (Cora and Hung, 2002) can be used. However, this source provides very limited information about the properties of wood fuel or type and size of the combustion technology in use that influence particulate emission levels from various systems. Many studies have been focusing on direct measurement and characterization of particulate emissions from wood burning district energy systems in order to quantify and explain the levels and parameters affecting the formation of air pollutants.

Table 4-3 summarizes the particulate emission levels reported from literature studying various wood fuels and combustion systems used in district heating system applications in terms of technology type and size. Studies in Table 4-3 are sorted out based on the fuel type and then combustion system.

**Table 4-3: Particulate emission levels in the flue gas of small and medium sized wood burning systems**

| Wood fuel type                             | Combustion system<br>(Capacity/ Load condition)        | Abatement system | Particulate level  | Measurement reference                          | Particulate level $mg/m^3$ * | Reference                      |
|--|--|------------------|--|--|------------------------------|--------------------------------|
| Wood pellets                               | Grate fired<br>(2 $MW_{th}$ )/ 100% load               | Multi- cyclone   | 50- 100  | $mg/Nm^3$ ,<br>at an average<br>7% to 9% $O_2$ | 57.8- 99.1                   | (Johansson et al.,<br>2003)    |
| Wood pellets                               | Grate boiler moving scrapes<br>(1.75 $MW$ )/ 100% load | Multi- cyclone   | 35   | $mg/MJ$ ,<br>at measured<br>8.9% $O_2$         | 72.9                         | (Johansson et al.,<br>2001)    |
| Wood pellets                               | Moving grate<br>(1.5 $MW_{th}$ )/ medium load          | Multi- cyclone   | 51 (fly ash),<br>44 (< 1 $\mu m$ ),<br>7 (1-5 $\mu m$ )  | $mg/Nm^3$ ,<br>at 13% $CO_2$                   |                              | (Wierzbicka et al.,<br>2005)   |
| Wood pellets                               | Moving grate<br>(1.5 $MW_{th}$ )/ high load            | Multi- cyclone   | 51 (fly ash),<br>41 (< 1 $\mu m$ ),<br>10 (1-5 $\mu m$ ) | $mg/Nm^3$ ,<br>at 13% $CO_2$                   |                              | (Wierzbicka et al.,<br>2005)   |
| Pellets                                    | Moving grate<br>(1.5 $MW_{th}$ )/ (0.3 $MW$ )          | Multi- cyclone   | 59   | $mg/Nm^3$ ,<br>at 13% $CO_2$                   | 53.1                         | (Lillieblad et al.,<br>2004)   |
| Wood briquettes                            | Grate boiler moving scrapes<br>(2.5 $MW$ )             | cyclones         | 40   | $mg/MJ$ ,<br>at measured<br>5.7% $O_2$         | 85                           | (L. Johansson et al.,<br>2001) |
| Dry wood (shaving,<br>sawdust, wood chips) | Moving grate<br>(1.5 $MW_{th}$ )/ (0.3 $MW$ )          | Multi- cyclone   | 48   | $mg/Nm^3$ ,<br>at 13% $CO_2$                   | 49.2                         | (Lillieblad et al.,<br>2004)   |
| Dry wood (shaving,<br>sawdust, wood chips) | Moving grate<br>(1.5 $MW_{th}$ )/ (0.9 $MW$ )          | Multi- cyclone   | 101  | $mg/Nm^3$ ,<br>at 13% $CO_2$                   | 104.2                        | (Lillieblad et al.,<br>2004)   |
| Dry saw dust                               | Moving grate<br>(1.5 $MW_{th}$ )/ low load             | Multi- cyclone   | 74 (fly ash),<br>63 (< 1 $\mu m$ )<br>11 (1-5 $\mu m$ )  | $mg/Nm^3$ ,<br>at 13% $CO_2$                   |                              | (Wierzbicka et al.,<br>2005)   |
| Dry saw dust                               | Moving grate<br>(1.5 $MW_{th}$ )/ medium load          | Multi- cyclone   | 63 (fly ash),<br>49 (< 1 $\mu m$ ),<br>14 (1-5 $\mu m$ ) | $mg/Nm^3$ ,<br>at 13% $CO_2$                   |                              | (Wierzbicka et al.,<br>2005)   |
| Dry saw dust                               | Moving grate<br>(1.5 $MW_{th}$ )/ high load            | Multi- cyclone   | 64 (fly ash),<br>44 (< 1 $\mu m$ ),<br>20 (1-5 $\mu m$ ) | $mg/Nm^3$ ,<br>at 13% $CO_2$                   |                              | (Wierzbicka et al.,<br>2005)   |

**Table 4-3: Particulate emission levels in the flue gas of small and medium sized wood burning systems (continued)**

| Wood fuel type             | Combustion system<br>(Capacity/ Load condition)     | Abatement system     | Particulate level  | Measurement reference        | Particulate level<br>$mg/m^3$ *           | Reference                     |
|----------------------------|---|----------------------|--|------------------------------|---|-------------------------------|
| Dry wood chips<br>(spruce) | moving grate boiler<br>(Water tube, 440 $kW_{th}$ ) | None                 | 50-100 (fly ash),<br>20 ( $< 1 \mu m$ )                                | $mg/Nm^3$ at<br>13% $O_2$    | 54-107 (fly ash),<br>21.5 ( $< 1 \mu m$ ) | (Obernberger et al.,<br>2001) |
| Wet wood chips<br>(spruce) | Moving grate boiler<br>(Water tube, 440 $kW_{th}$ ) | None                 | 50-200 (fly ash),  | $mg/Nm^3$ at<br>13% $O_2$    | 54-211(fly ash),                          |                               |
| Wet wood chips             | Bubbling fluidized bed<br>(4 $MW_{th}$ / 90% load)  | ESP                  | 2.3 (fly ash)  | $mg/Nm^3$ at<br>11% $O_2$    | 2.5 (fly ash)                             | (Raili and Martti,<br>1996)   |
| Wet forest residues        | Moving grate burner<br>(6 $MW$ )/ 4.5-5 $MW$ load   | ESP                  | 15.8 (fly ash),<br>13.2 (0.03-1.0 $\mu m$ ),<br>2.6 (1.0-6.8 $\mu m$ ) | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Strand et al., 2002)         |
| Wet forest residues        | Moving grate burner<br>(6 $MW$ )/ 4.5-5 $MW$ load   | ESP and<br>condenser | 8.2 (fly ash),<br>1.8 (0.03-1.0 $\mu m$ ),<br>6.3 (1.0-6.8 $\mu m$ )   | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Strand et al., 2002)         |
| Wet forest residues        | Moving grate burner<br>(6 $MW$ )/ 4.5-5 $MW$ load   | Multicyclone         | 134.9 (fly ash),<br>76.3 ( $< 0.8 \mu m$ ),<br>58.5 (0.8-6 $\mu m$ )   | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Strand et al., 2002)         |
| Forest residues            | Moving grate<br>(1 $MW_{th}$ )/ medium load         | Multi- cyclone       | 120 (fly ash),<br>117 ( $< 1 \mu m$ ),<br>3 (1-5 $\mu m$ )             | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Wierzbicka et al.,<br>2005)  |
| Forest residues            | Moving grate<br>(1 $MW_{th}$ )/ high load           | Multi- cyclone       | 185 (fly ash),<br>100 ( $< 1 \mu m$ ),<br>85 (1-5 $\mu m$ )            | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Wierzbicka et al.,<br>2005)  |
| Wet forest residues        | Moving grate boiler<br>(1 $MW$ / 80% load)          | multi-cyclone        | 218 (fly ash),<br>100 ( $< 1 \mu m$ ),<br>118 (1-10 $\mu m$ )          | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Raili and Martti,<br>1996)   |
| Wet forest residues        | Moving grate boiler<br>(1 $MW$ / 60% load)          | multi-cyclone        | 150 (fly ash),<br>145 ( $< 1 \mu m$ ),<br>5.3 (1-10 $\mu m$ )          | $mg/Nm^3$ ,<br>at 13% $CO_2$ |   | (Pagels et al., 2003)         |

**Table 4-3: Particulate emission levels in the flue gas of small and medium sized wood burning systems (continued)**

| Wood fuel type                 | Combustion system<br>(Capacity/ Load condition)   | Abatement system | Particulate level   | Measurement reference   | Particulate level<br>$mg/m^3$ *                               | Reference                         |
|--------------------------------|---|------------------|---|---|---|-----------------------------------|
| Wet forest residues            | Moving grate boiler<br>(1 MW/45% load)  | multi-cyclone    | 122 (fly ash),<br>117 (<1 $\mu m$ ),<br>5.1 (1-10 $\mu m$ ) | $mg/Nm^3$ ,<br>at 13% $CO_2$                                  |   | (Pagels et al., 2003)             |
| Wet forest residues            | Moving grate boiler<br>(6 MW/ 85% load)   | multi-cyclone    | 157 (fly ash),<br>79 (<1 $\mu m$ ),<br>78 (1-10 $\mu m$ )   | $mg/Nm^3$ ,<br>at 13% $CO_2$                                  |   | (Pagels et al., 2003)             |
| Wet forest residues            | Grate boiler<br>(1 and 6 MW)  | cyclone          | 25-100 (<1 $\mu m$ )  | $mg/Nm^3$ ,<br>$O_2$ or<br>$CO_2$ percentage<br>not specified |   | (Lillieblad et al.,<br>2001)      |
| Wood residue                   | Two stage gasifier-<br>combustor system<br>(Cogeneration- 17.5<br>$MW_{th}$ and 1.38 $MW_e$ ) | ESP              | 2.5   | $mg/Nm^3$ ,<br>$O_2$ or<br>$CO_2$ percentage<br>not specified |   | (Nexterra systems<br>corp., 2009) |
| 80% willow/ 20%<br>wood pellet | Circulating fluidized bed<br>(3-12 MW at 8-9 $MW_{th}$ fuel<br>thermal effect)                | Cyclone          | 410 (fly ash),<br>75 (< 1 $\mu m$ ),<br>335 (> 1 $\mu m$ )  | $mg/Nm^3$ ,<br>at an average<br>3.7% $O_2$                    | 440 (fly ash)<br>80.5 (< 1 $\mu m$ ),<br>359.5 (> 1 $\mu m$ ) | (Valmari et al., 1998)            |
| Bark                           | Moving grate boiler<br>(Water tube, 440 $kW_{th}$ )   | None             | 400- 500 (fly ash),<br>60 (< 1 $\mu m$ )                    | $mg/Nm^3$ at<br>13% $O_2$                                     | 429-537 (fly ash),<br>64.4 (< 1 $\mu m$ )                     | (Oberberger et al.,<br>2001)      |
| Waste wood                     | Moving grate boiler<br>(Water tube, 440 $kW_{th}$ )   | None             | 300-400 (fly ash),<br>160 (< 1 $\mu m$ )                    | $mg/Nm^3$ at<br>13% $O_2$                                     | 322-429 (fly ash),<br>171.7 (< 1 $\mu m$ )                    | (Oberberger et al.,<br>2001)      |

\* Numbers are converted to 20°C, 101.325 kPa, dry gas and 8%  $O_2$  concentration which is the standard condition considered in Vancouver's bylaw. The particulate emission limit in Vancouver is 18  $mg/m^3$ . Mass balance conversion process from (Van Loo and Koppejan, 2008) has been used in order to convert  $mg/MJ$  unit to  $mg/m^3$ . When not stated, information about the flue gas and/or fuel composition has not been sufficient in the original paper in order to convert to the reference condition.

Combustion of high quality wood pellets derived from natural stem wood in grate boiler district heating systems (1.5-2.5 MW) produces particulate emissions between 50 and 100 mg/m<sup>3</sup> (20°C, 101.325 kPa, dry gas and 8% O<sub>2</sub>) downstream of a multi-cyclone (Johansson et al., 2001; Johansson et al., 2003; Lillieblad et al., 2004; Wierzbicka et al., 2005). These studies also extended their analyses to include the effect of varying fuel properties, fuel load, and excess air ratio on emission levels. Some as well included compositional analysis of the particles. In district heating wood pellet grate boilers, increase in excess air would not increase the mass concentration of particles in the flue gas (Johansson et al., 2001; Johansson et al., 2003; Wierzbicka et al., 2005). However, decrease in the load and excess air would shift the particle sizes towards larger particles due to increase in soot formation and agglomeration of these particles (Johansson et al., 2001; Johansson et al., 2003). In the sub-micron range also inorganic elements of potassium, sulphur, and chlorine were dominant with small amounts of sodium, magnesium, and zinc (Johansson et al., 2001; Johansson et al., 2003; Lillieblad et al., 2004). Johansson et al. (2001) found that utilizing wood pellets with lower density than the standard value increases the amount of CO and unburnt carbon as well as particles mass concentration in the flue gas. Easier disintegration of low-density fuels during early stages of combustion is a possible explanation for this observation (Johansson et al., 2003). However, neither of the studies identified a clear tendency of higher number concentration of particles when lower density wood pellets were used (Johansson et al., 2003), (Johansson et al., 2001). Mass concentration of particulate emissions from wood briquette combustion in district heating grate boiler is very well comparable to the wood pellets boilers (Johansson et al., 2001). In this case, the increase in mass concentration of particles in the flue gas is notably higher when excess air increases compared to the case of wood pellets (Johansson et al., 2001; Johansson et al., 2003). Also using low density briquettes would increase the number concentration of particles in the flue gas (Johansson et al., 2001).

Utilization of dry wood material (shavings, sawdust, wood chips) with moisture content below 10% (wt.) in a 1.5 MW moving grate boiler result in particulate emission levels comparable to wood pellets combustion under the same condition (Lillieblad et al., 2004). However, the mass concentration of particulate emissions from combustion of dry

wood material at medium load would be almost double than the amount generated at low load (increasing load from 0.3 MW to 0.9 MW) (Lillieblad et al., 2004).

Combustion of dry saw dust (10% wt. moisture content) under low, medium, and high load conditions in a 1.5 MW moving grate boiler showed that increase in boiler load slightly increases the concentration of coarse mode particles in the fly ash. Also, particle emission levels from dry saw dust combustion were relatively close to the emission levels from wood pellet combustion under similar combustion conditions (results from dry saw dust combustion were about 10 mg/Nm<sup>3</sup>, 13% CO<sub>2</sub>, higher than the case of wood pellets) (Wierzbicka et al., 2005).

Utilization of dry wood chips (moisture content ~10% wt.) in a 440 MW moving grate boiler generates particle matter emissions much lower than that of using wet wood chips (moisture content ~50% wt.) (Oberberger et al., 2001). They also found the tendency of higher coarse mode fly ash formation with increasing the plant load while they could not identify such a tendency for the aerosol mode fly ash. They related this observation to higher possibility for ash entrainment from the fuel bed when air and fuel flow is higher. Using an ESP during the combustion of wet wood chips in a bubbling fluidized bed would reduce particulate emission levels to 2.5 mg/Nm<sup>3</sup>, 8% O<sub>2</sub>, far below 18 mg/Nm<sup>3</sup>, 8% O<sub>2</sub> emission limit (Raii and Martti, 1996).

Combustion of low quality wood fuel, such as forest residues, bark, wood waste, or co-firing of willow, in moving grate boilers produces particulate emissions remarkably higher than that of wood pellets or dry saw dust and wood material (Lillieblad et al., 2001; Pagels et al., 2003; Raii and Martti, 1996; Strand et al., 2002; Valmari et al., 1998; Wierzbicka et al., 2005). Combustion of willow (co-fired with 20 wt% wood pellets) in a 12 MW circulating fluidized bed boiler with a cyclone resulted in submicron flying ashes which were mainly sulphate particles (Valmari et al., 1998). Study of fine mode particles (<1 µm) in the flue gas of moist forest residues combusted in 1 and 6 MW grate boilers downstream of cyclones was carried out by Lillieblad et al. (2001). They observed that potassium, chlorine and sulphur dominate the elemental composition of fine mode particles. They also tested the collection efficiency of an ESP cleaning system on the flue gas of moist forest residues combustion and observed a U shape collection efficiency

curve with minimum on particles between 100 to 1000 nm size ranges (Lillieblad et al., 2001). Strand et al. (2002) measured and analyzed particulate emissions downstream of an ESP flue gas cleaning system with collection efficiency of at least 96% both in the fine and coarse particle ranges on a 6 MW moving grate boiler firing wet forest residues. The main elements they found in the fine fraction of the particles were K, S, and Cl, and Zn which constituted 90% of the analyzed elements in the fine mode. In the coarse fraction of the particles Ca, Fe, and Mn were dominant (40-50% of the coarse particles mass) (Strand et al., 2002). Due to the wood elements in low quality wood fuel, it would be difficult to limit the amount of particulate matter emissions even when a high efficiency flue gas cleaning system is used.

Grate boilers are the most commonly studied technology used in wood burning district energy systems. Operation of boilers under optimum designed condition is a key parameter in achieving controlled emission levels from biomass combustion. Reducing fuel load to levels below design range can cause higher coarse particle formation due to soot formation and higher possibility of condensation. Also, higher fuel load or higher excess air than the design range can increase the formation of coarse particles in the flue gas.

Gas cleaning systems can be utilized in order to significantly reduce the amount of particulate emissions in the wood combustion flue gas. Cyclones are widely used in district heating centres as a primary gas cleaning system to significantly reduce the amount of coarse fly ash particles. The collection efficiency of cyclones for particle diameters below 5  $\mu\text{m}$  is very limited. Knowing that particle emissions from wood combustion have two dominant peaks in both coarse and fine size ranges make it necessary to use flue gas cleaning systems with high collection efficiencies in the sub-micron particle size range. Electrostatic precipitator or baghouse systems have collection efficiency in the sub-micron particle size range well above 95% which can be installed downstream from a cyclone system.

Grate burners are able to utilize a wide variety of wood fuels and moisture content range. It can be understood from Table 4-3 that without an efficient gas cleaning technology such as an ESP or a baghouse, grate firing of all types of wood fuel would

result in PM emissions above the regulatory emission level in Vancouver, BC. Combustion of natural uncontaminated wood fuel or processed wood fuels, such as wood pellets, wood briquettes, and dry sawdust and shavings, in grate burners would result in lower amount of particulate emissions compared to that of wet wood fuel such as forest residues. For grate firing of wood pellets, installation of an ESP or a baghouse system which can reduce particulate emission levels in the flue gas under normal operation condition well above 90%, would be necessary in order to meet the 18 mg/Nm<sup>3</sup> regulatory limit in Vancouver, BC. Complying with the foregone regulatory limit using bark or logging residues is an issue. These materials will produce particulate emissions above 100 mg/Nm<sup>3</sup> and may be as high as 500 mg/Nm<sup>3</sup>. High natural content of alkali and heavy metals in bark and logging residues results in uncontrolled vapors of toxic emissions in the fine mode of flue gas from direct combustion of these materials. Therefore, grate combustion of such material for district heating applications in populated area is not recommended.

Review of previous studies that measured the particulate matter emissions from wood burning district heating facilities revealed that limited research has been done on technologies such as suspension burner, fluidized bed and two-stage gasification technologies. These technologies have been used in wood biomass district energy systems recently. Reference (Nexterra systems corp., 2009) is an exception which is manufacturer's reported emission level from a two-stage gasification-combustion technology. Most previous studies focused on the grate firing of mixed biomass with only cyclone gas cleaning systems which is the most practiced technology in district energy centres. More research efforts are required for quantification of emission levels from alternative combustion technologies such as powder burner and gasification technologies. Although efficiency of ESP and baghouse cleaning systems have been studied widely, more studies focusing on direct measurement of particulate emissions from wood burning district heating systems that utilize these high efficiency gas cleaning systems can contribute significantly to addressing the public concern about such a practice. Also, systems to detect impregnated wood with harmful chemical and fractionate wood into suitable and unsuitable feedstock needs to be developed.

## 4.5. Conclusions

In this chapter, various factors leading to formation of particulate matter emissions from combustion of wood biomass used in district heating applications were explained based on the literature survey. Special attention was paid to the direct measurement levels of particulate emissions, as well as the effect of wood fuel characteristics and combustion fuel load on the formation of particulate matters.

It was concluded that wood fuel quality, which is defined by both physical properties and chemical composition, has direct impact on the formation of submicron as well as super-micron particle emissions. Utilizing high quality wood fuel is the primary consideration in order to assure limited particulate emissions especially in the submicron particle size range. High quality solid wood fuel is produced from natural stem wood free of impurities, such as preservatives, glue, paint, salt, sand, etc., and has low moisture content. Wood fuel from non-stem wood, such as bark, contains high ash and alkali and heavy metal contents.

Among various types of available wood fuel, direct combustion of high quality wood fuel such as wood pellets produced from natural, uncontaminated stem wood generates the least amount of PM emissions both in the sub-micron and super-micron size ranges. Grate firing of wood pellets under normal operating condition would reportedly result in particle emissions in the range of about 50-100 mg/m<sup>3</sup> (20°C, 101.325 kPa, dry gas and 8% O<sub>2</sub>) downstream of a multi-cyclone. Cyclones are more efficient for primary dust reduction purposes in order to eliminate coarse particulates from the flue gas. Therefore, efficient gas cleaning systems, such as ESPs or baghouses should be implemented downstream of the cyclone system in wood burning district heating systems in order to meet the stringent particulate regulatory emission limit introduced in Vancouver, BC. Implementation of efficient abatement systems with more than 90% collection efficiency, will reduce the particulate emissions of wood pellet grate combustion to 5-10 mg/m<sup>3</sup> (20°C, 101.325 kPa, dry gas and 8% O<sub>2</sub>) levels in the flue gas, well below the regulatory limit. Grate combustion of low quality wood fuels such as logging residues and bark is not recommended for district heating centres located in populated areas because of not

only emission levels above 300 mg/m<sup>3</sup> (20°C, 101.325 kPa, dry gas and 8% O<sub>2</sub>) but also possibility of uncontrolled toxic vapors presence in the flue gas during combustion.

## **Chapter 5. Techno-economic analysis of renewable energy source options for a district heating project \***

### **5.1. Synopsis**

Wood pellets in BC are produced from ground natural wood. Wood pellets are densified wood with high quality characteristics for combustion purposes; energy density of 2756 kWh/m<sup>3</sup>, moisture content of about 7%, an individual particle density of 1.2 g/cm<sup>3</sup>, with low ash content (about 0.5%) (Oberberger, 1998). Compared to other wood biomass sources that are commonly used for heat production, such as wood chips (moisture content >30%, energy density of 785- 855 kWh/m<sup>3</sup> (Oberberger, 1998), wood pellets have higher energy density and lower moisture content. This gives the ability to economically transport wood biomass over longer distances as less water and more fuel are being transported.

The objective of this chapter is to evaluate the economic performance of three types of technology options that can utilize wood pellets for heat production purpose: moving grate boiler, gasification system, and powder burner. Moreover the cost of heat produced by these technologies is compared to those of natural gas, sewer heat recovery, and geothermal options. Installation of high efficiency ESP system for flue gas cleaning is considered for the wood pellet technologies. The cost of produced heat from each system is calculated for the base-load and peaking/backup systems separately.

### **5.2. Energy demand profile**

In order to estimate the annual fuel/energy requirement of the district heating system, energy demand profile of the district heating system should be calculated.

In order to estimate the energy load demand for space heating, two distinct methods can be used. One way is to calculate the energy required to maintain interior temperature at human's comfort level of 18- 20 °C, knowing the heat transfer ratio and heat losses

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\* A version of this chapter has been accepted for publication. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Melin, S. (2009), Techno-economic analysis of renewable energy source options for a district heating project. International Journal of Energy Research, DOI: 10.1002/er.1637.

occurred in different parts of the building (ASHRAE, 2005). This method is generally used for the purpose of heat demand estimation at the design level and requires a set of information about buildings designs and specifications which may not be available at early stages of district heating feasibility analysis. The alternative way is to use the historically observed energy consumption patterns from similar type of buildings in the same region, which can be collected from field surveys or installed energy management systems at the site (Dalton et al., 2008; Dalton et al., 2009; Nijjar, 2005). This method is currently used in a number of commercial software such as HOMER (Lambert and Lilliental, 2004) and gives a rough estimate of the average and peak energy demand per area unit (Energy Use Intensity- EUI) requirement of an archetypal building. Monthly average heat demand of the district can be estimated using Equation 5-1:

$$Q_j = \sum_i EUI_{i,j} \times A_i \quad 5-1$$

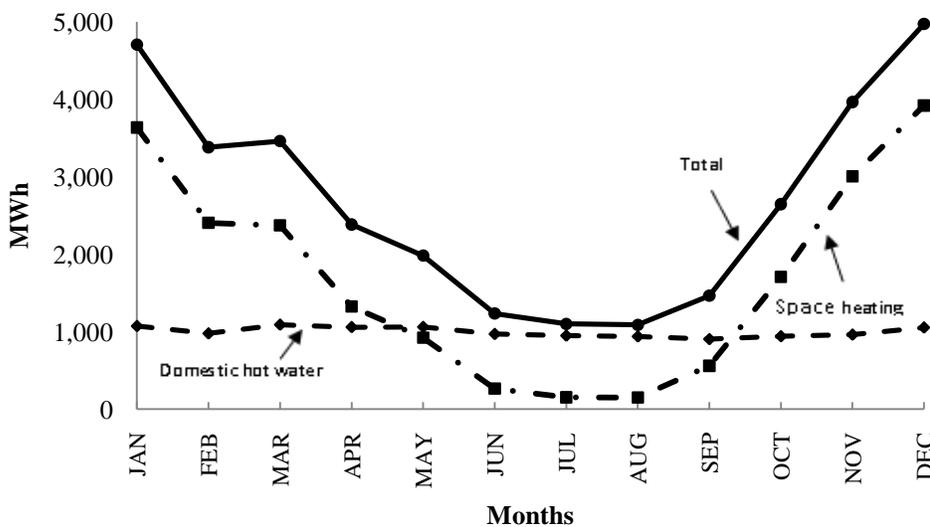
Where  $Q_j$  is the total community's heat demand in month  $j$ ,  $j= 1, \dots, 12$ ,  $EUI_{i,j}$  is the average heat demand per unit area (EUI) of building type  $i$  in month  $j$ , and  $A_i$  is the total heated area of building type  $i$ .

The Southeast False Creek community was a new development area and much of the information about building designs and specifications were not available or poorly developed. Monthly average energy used for space heating and domestic hot water for different types of buildings were retrieved from energy management database of an energy company consulting energy projects in the Vancouver area, BC (Chin, 2008). Table 5-1 shows the average space and hot water heating requirement of archetypal buildings:

**Table 5-1: Energy use intensity of space and hot water requirements (combined) for various archetypal buildings Source: (Chin, 2008)**

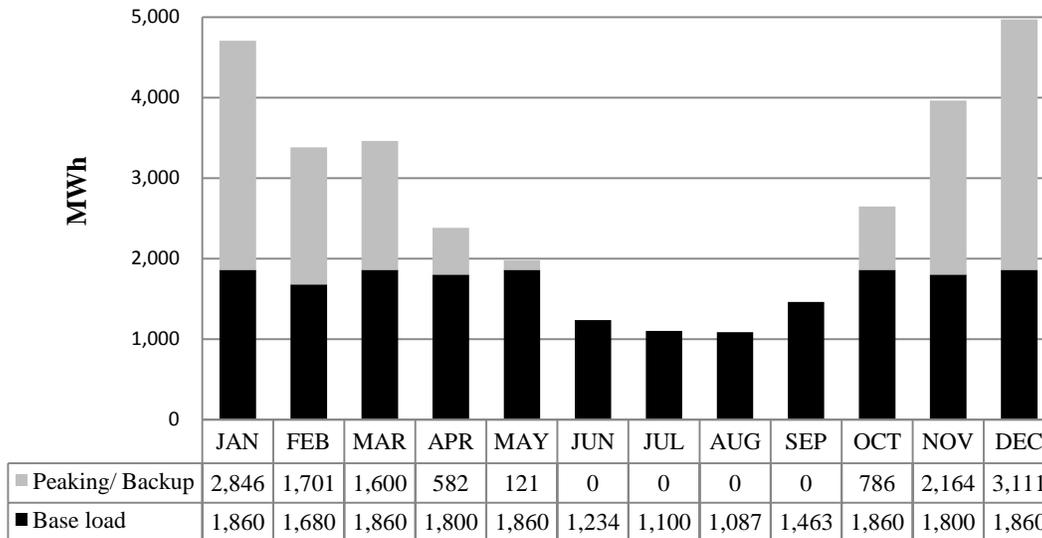
| Month        | $EUI_{i,j}(kWh/m^2)$ |      |      |     |     |     |     |     |     |      |      |      |
|--------------|----------------------|------|------|-----|-----|-----|-----|-----|-----|------|------|------|
|              | Jan                  | Feb  | Mar  | Apr | May | Jun | Jul | Aug | Sep | Oct  | Nov  | Dec  |
| School       | 9.5                  | 6.8  | 6.5  | 4.4 | 2.6 | 1.5 | 1.3 | 1.3 | 2.1 | 5.3  | 8.0  | 9.4  |
| Office       | 11.5                 | 7.2  | 6.5  | 3.5 | 1.8 | 1.2 | 1.2 | 1.3 | 1.6 | 5.1  | 9.2  | 11.7 |
| Retail store | 6.8                  | 5.3  | 5.4  | 3.7 | 2.3 | 1.8 | 1.8 | 1.9 | 2.1 | 4.2  | 5.8  | 7.6  |
| High-rise    | 18.4                 | 13.4 | 13.9 | 9.7 | 7.2 | 5.1 | 4.5 | 4.4 | 6.1 | 10.6 | 15.6 | 19.4 |
| Low-rise     | 16.7                 | 12.4 | 12.6 | 8.9 | 6.8 | 5.0 | 4.5 | 4.4 | 5.7 | 9.6  | 14.1 | 17.7 |

Figure 5–1 shows the estimated energy profile of the community throughout the year.



**Figure 5–1: Energy demand profile of the Southeast False Creek community**

The total required heat from the district heating system would be 32,377 MWh/yr. The heating load of the district heating system has been proposed to be provided by a combination of base-load and peaking/backup systems (FVB Energy Inc., 2006b). It was proposed to have a 2.5 MW base-load system which operates at full capacity most of the times during the year (capacity factor of 89%). The peaking/ backup system would be a 10 MW natural gas boiler to operate at heat-match mode (capacity factor of 15%). The thermal energy required by the community would be produced by the base-load system and if excess demand is observed, the peaking system would cover the excess. Figure 5–2 shows the total heating energy produced by each system during the year which is calculated based on the load profile of the community.



**Figure 5–2: Share of heating energy production between base- load and peaking/ backup system during the year**

On average, 60% of the heat and hot water requirement of the district would be provided by the base-load system and 40% of that by the peaking/ backup system. Although various base-load capacities could be considered, it should be noted that optimizing the base-load/ peaking capacity ratio has been beyond the scope of this study. The suggested 2.5/10 base-load/ peaking capacity ratio is taken into account as a given number which has been the actual considered capacities in the studied case.

### 5.3. Energy technology options

The natural gas boilers considered for peaking/ backup and the base-load systems are from low- NO<sub>x</sub> type with 81% efficiency (Payne and Thompson, 1996) when operating within the designed input capacity range. Peaking systems are either off or operating at partial load, which reduces boiler’s efficiency (Payne and Thompson, 1996).

In order to convert wood pellets into useable thermal energy, they should be combusted directly or in a stepwise manner. Main combustion technologies used to produce heat from biomass include: (1) grate stoker burners, and (2) fluidized bed combustors, (3) powder burners, and (4) two-stage combustion system (gasification) (Bain et al., 1998; Nussbaumer, 2003; Van Loo and Koppejan, 2008).

In the grate stoker burners, a stoker spreads wood biomass on a stationary sloping, vibrating, or moving grate on which combustion takes place (Bain et al., 1998). In these burners, the grate is responsible for lengthwise transport of fuel and distribution of the primary air. Grate stroke boilers are the most common biomass combusting systems for energy production purposes. Compared to grate systems, fluidized bed combustion systems have higher capital and operating costs which make them more attractive for plants over 20  $MW_{th}$  (Van Loo and Koppejan, 2008). Fluidized bed combustion systems are thus not considered in this study.

In powder burners, fine particles of pulverized wood are pneumatically injected into the furnace (Van Loo and Koppejan, 2008) where combustion takes place under controlled staged-air circumstances in three phases: 1) devolatilisation to char and volatiles, 2) combustion of the volatiles, and 3) combustion of the char (Williams et al., 2001). Wood pellets need to be grinded to powder (particle size  $< 2\text{ mm}$ ) (Spliethoff and Hein, 1998) in a hammer mill prior to feeding to the suspension burners. Powder burners may be designed to handle different fuel types in various modes of solid, liquid, or gas. An example is a wood powder suspension burner with the ability to switch to natural gas. This increases the fuel security over the service life of the boiler since in the shortage of wood biomass, it would be possible to use natural gas.

The two-stage combustion technology is based on a thermo-chemical reaction called gasification. At first, under partial oxidization condition at high temperatures, biomass is converted into a combustible gas mixture called syngas. Syngas produced from a downdraft, air-blown technology has higher heating value of 5.7 MJ/  $Nm^3$  (Bridgwater et al., 2002). In terms of syngas quality (tars and dust content), downdraft technologies have better performance than fluidized bed or updraft technologies (Bridgwater et al., 2002). This syngas can be burnt directly in an oxidizer attached to a boiler for hot water or steam generation (McKendry, 2002). The two- stage gasification system has got an increasing attention in BC in recent years with a few district heating systems now installed and operating in various parts of the province.

In the case of geothermal and sewer heat sources, a heat pump/exchanger system transports and converts the heat available from these sources into useable thermal energy. Heat source is an important component of a heat pump which has high influence on

performance and economy of the heat pump system (Berntsson, 2002). Heat pumps are electricity intensive part of the system. The coefficient of performance (COP) of heat pumps depends on various factors related to both the heat source condition and the heat pump design. The COP measure is a ratio representing energy output to energy input. American Refrigeration Institute (ARI) directory contains equipment with COP ranges from 2.8 to 3.6 (Lienau, 1997). Typical ground source heat pump in Canada has a COP in the range of 2.9-3.2 (Healy and Ugursal, 1997). Sewer heat is advantageous compared to ground heat as it offers higher COP ranges compared to that of ground heat (Berntsson, 2002).

Table 5-2 summarizes technology options for peaking and base-load systems, their fuel sources, and efficiencies.

**Table 5-2: Technology options, fuel sources, and efficiencies considered for peaking/ backup and base-load systems**

|                 | Technology                | Energy source | Efficiency | Source   |
|-----------------|---------------------------|---------------|------------|--|
| Peaking/ backup | Gas fired boiler          | Natural gas   | 75%        | (Payne and Thompson, 1996)                     |
| Base-load       | Gas fired boiler          | Natural gas   | 81%        | (Payne and Thompson, 1996)                     |
|                 | Sewer heat recovery       | Sewage heat   | 3.5        | (Lienau, 1997; Healy and Ugursal, 1997)        |
|                 | Geothermal heat exchanger | Ground heat   | 2.5        | (Lienau, 1997; Healy and Ugursal, 1997)        |
|                 | Moving grate              | Wood pellets  | 75%        | (Energy and Environmental Analysis Inc., 2007) |
|                 | Fixed bed gasifier        | Wood pellets  | 65%        | (Energy and Environmental Analysis Inc., 2007) |
|                 | Powder burner             | Wood pellet   | 86%        | (Payne and Thompson, 1996)                     |

## 5.4. Economic study

The economic comparison of different energy options for district heating system is made based on the present value (2009 base year) of the produced energy cost. The energy production cost stems from capital investment and operating and maintenance costs (O&M). Cost burdens to or revenues from the district heating system that are the same for all options are not considered in this analysis. Examples of these factors include revenues from energy sales, income taxes, district heating network capital and operating

costs, hot water pump stations, and funding and ownership options. Although these factors affect the economics of the district heating system as a whole, it is assumed that any figure considered for these factors would have the same economic effects on all energy options.

#### 5.4.1. Capital cost

Table 5-3 lists initial investments required for a 10 MW natural gas boiler and several options for the 2.5 MW base-load system.

**Table 5-3: Initial investment required for energy option alternatives**

| Item description<br>(2009, 1000 CAD) <sup>a</sup> | Peaking <sup>b</sup> |                 | Base-load <sup>b</sup> |                  |                   |                  |                  |
|---|----------------------|-----------------|------------------------|------------------|-------------------|------------------|------------------|
|   | NG <sup>d</sup>      | NG <sup>d</sup> | WPGB <sup>d</sup>      | WPG <sup>e</sup> | WPPB <sup>f</sup> | SHR <sup>d</sup> | GHE <sup>d</sup> |
| Land  | 232                  | 28              | 86                     | 114              | 127               | 157              | 90               |
| Building  | 804                  | 129             | 523                    | 623              | 673               | 544              | 253              |
| Major equipment                                   | 798                  | 328             | 1,538                  | 2,287            | 1,984             | 5,522            | 7,760            |
| Electrical Installation                           | 347                  | 53              | 45                     | 114              | 79                | 772              | 723              |
| Mechanical Installation                           | 1,020                | 154             | 708                    | 867              | 802               | 753              | 678              |
| Design engineering                                | 386                  | 59              | 369                    | 447              | 380               | 569              | 456              |
| General contractor                                | 326                  | 51              | 292                    | 360              | 351               | 445              | 355              |
| Plant total                                       | 4,314                | 857             | 3,776                  | 5,078            | 4,556             | 9,064            | 10,481           |

<sup>a</sup> Numbers are rounded to 1000 CAD, the effect of rounding was less than 0.1% to the total plant cost.

<sup>b</sup> NG: natural gas boiler, WPGB: wood pellet moving grate burner, WPG: wood pellet gasifier and oxidizer, WPPB: wood pellet powder burner, SHR: sewer heat recovery system, GHE: geothermal heat exchange system.

<sup>d</sup> (FVB Energy Inc., 2006b)

<sup>e</sup> (Riionheimo)

<sup>f</sup> (Energy and Environmental Analysis Inc., 2007)

The major equipment for the peaking system is a 10 MW natural gas boiler. The 2.5 MW natural gas option would have the opportunity to use the infrastructure developed for the peaking system within the energy centre which results in less costly installation and construction. Common equipment used in all the wood pellet systems include wood pellet storage silo, multi-cyclone, and electro static precipitator (ESP). In addition, wood pellet grate burner system include a moving grate burner and boiler, wood pellet gasifier includes a fixed bed gasifier, oxidizer and boiler, and wood pellet powder burner include a hammer mill and powder burner and boiler. Major installation for the sewage heat recovery system includes heat exchanger, heat pump, interconnecting piping between treatment equipment and heat pump, cooling tower evaporator, and sewage pretreatment

unit which consists of self cleaning screens, booster pumps, backwash pits, transfer pumps, stainless steel wetted construction, and odor control unit. Major components of the geothermal exchange system are the heat exchanger, heat pump, geothermal wells (vertical trench), and required interconnecting piping between the wells and plant. The general contractor costs include construction and supervision costs. The total plant cost includes 10% contingency. It should be noted that the district heating system includes the natural gas peaking system together with one of the base-load options.

For the base-load system, initial costs associated with the natural gas technology are cheaper than that of renewable technologies. This is due to the less costly equipment and the opportunity to share the developed infrastructure with the peaking system. Among the renewable technologies, sewage heat recovery and geothermal heat exchange systems cost almost twice as much as wood pellet heat conversion technologies.

#### **5.4.2. Operating and maintenance costs**

The main operational expenses of the energy options include fuel or energy cost, maintenance cost, and the cost of operating staff. The cost of staff is considered in the operating costs of the peaking/ backup system. Tax savings due to depreciation and operating costs of the systems are also included in the analysis. The basic assumptions made for calculating the present value (2009 CAD) of the annual operating costs of different energy systems are shown in Table 5-4.

**Table 5-4: Economic assumptions for calculating the present value of O&M cost of energy options**

| Parameter                                    | value  |
|--|--|
| District heating service life (yr)           | 25   |
| Discount rate (%) <sup>a</sup>               | 10   |
| Building depreciation rate (%) <sup>b</sup>  | 5  |
| Equipment depreciation rate (%) <sup>b</sup> | 30   |
| Annual inflation rate (%) <sup>c</sup>       | 2.15   |
| Natural gas price (CAD/MWh) <sup>d</sup>     | 37.47 (year 2009)                                    |
| Wood pellet price (CAD/MWh) <sup>e</sup>     | 24.28 (year 2009)                                    |
| Electricity price (CAD/MWh) <sup>f</sup>     | 55.0   |
| Maintenance (CAD/yr)                         | 1 or 2% of the total plant cost <sup>g</sup>         |
| Staff salary (CAD/hr) <sup>h</sup>           | 20 for operating staff, 35 for professional engineer |
| Corporation tax rate <sup>i</sup>            | 30%  |

<sup>a</sup> (Compass Resource Management Ltd., 2006)

<sup>b</sup> declining balance method, (Starky, 2006).

<sup>c</sup> Average inflation for the past 10 years (Bank of Canada, 2008).

<sup>d</sup> (Terasen gas Inc., 2009)

<sup>e</sup> Delivered at the plant (Chau et al., 2009)

<sup>f</sup> (BC Hydro, 2009)

<sup>g</sup> 1% for Natural gas, sewer and geothermal systems; 2% for wood pellet systems.

<sup>h</sup> (Chau et al., 2009)

<sup>i</sup> <http://www.cra-arc.gc.ca/tx/bsnss/tpcs/crprtns/rts-eng.html>

In this study, in order to predict the natural gas price over the 25-year service life of the district heating centre, a regression model using historical data from July 2000 to March 2009 obtained from Terasen Gas Inc. is estimated and employed ( $y = 8.8095 + 0.0166x$ , where  $y$  is the natural gas price in CAD/GJ and  $x$  is the year starting from year 11) (Terasen gas Inc., 2009). The yearly average price is used in the analysis in order to avoid the short term fluctuations of the natural gas price. The annual inflation rate for the electricity and wood pellets is assumed to be 3% and 2%, respectively.

The powder burner facility requires a hammer mill to grind wood pellets into the desired particle size prior to entering the furnace. Esteban and Carrasco (Esteban and Carrasco, 2006) found literature references regarding the energy consumption of biomass grinding not only very scarce, but also varying a lot depending on the feed material and machinery properties. Holtzapple et al. (2004) reported the electrical energy requirement for grinding poplar wood chips of  $25.4 \times 6.4$  mm in size up to fine particles of 2 mm in a hammer mill of about 50 KWh/t. For the powder burner option, the fuels include the

wood pellets and the electricity used to operate the hammer mill, therefore the fuel cost covers the wood pellet cost plus the electricity cost for grinding them.

Annual fuel consumption for each energy option is calculated based on Equation 5-2:

$$\text{Total annual fuel consumption} = \frac{\text{Annual heat produced by the system}}{\text{System efficiency}} \quad 5-2$$

Where the total annual fuel consumption and annual heat production by the system are stated in *MWh/yr*. For the case of heat pump options, the COP factor is used as system efficiency in order to calculate the annual electricity requirement.

Staff requirement for the facility includes a 24/7 operating staff and a full time boiler engineer (certificate holder), staff salaries are considered in the operating costs of the peaking/ backup system.

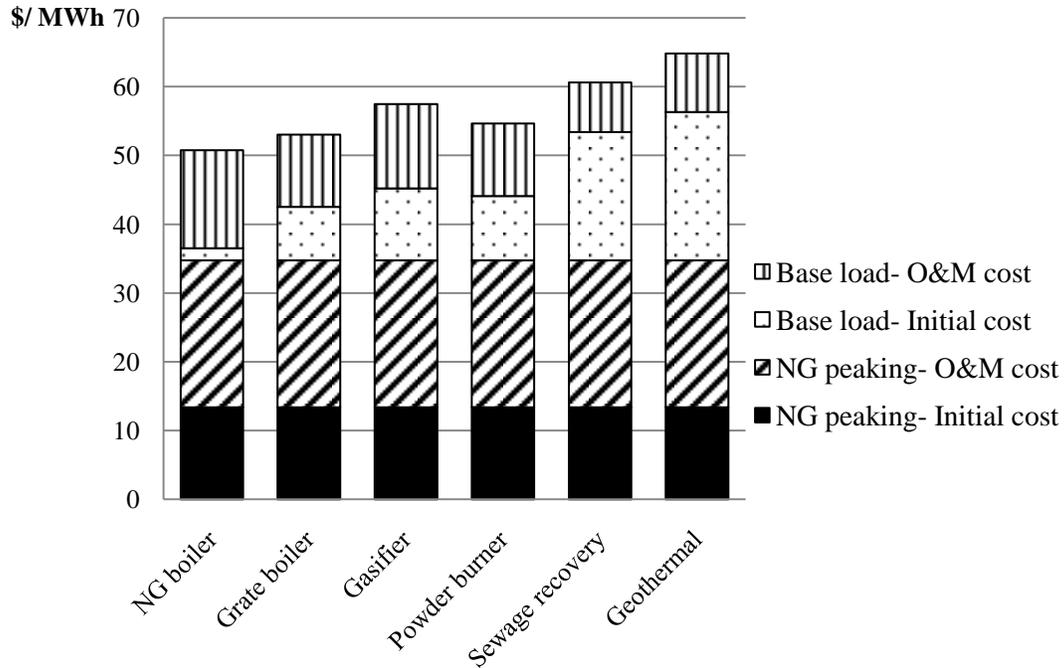
In order to calculate the present value (2009 CAD) of the operating and maintenance (O&M) and depreciation costs, Equation 5-3 is used (Fraser et al., 2006):

$$P = \sum_{n=1}^{25} (OM_n - D_n) \times \frac{(1+i)^n - 1}{i(1+i)^n} \quad 5-3$$

Where  $P$  is the present value of the annual costs,  $n$  is the period (e.g. for one year, year 2010,  $n = 1$ ),  $OM_n$  is the total O&M cost for period  $n$ ,  $D_n$  is the total depreciation for period  $n$ , and  $i$  is the discount rate. The salvage value of building and equipment at the end of the service life is calculated using the declining-balance depreciation method. Also the resale price of land at the end of the service life of the project is estimated using the general inflation rate and is considered in the cash flow analysis.

## 5.5. Cost of energy options

Figure 5–3 shows the cost of produced energy over 25-year service life of the district heating plant. For the peaking/ backup system, the cost of the of the system has been divided by the total heat produced by this system, and the base- load system cost has also been divided by the total heat produced by that system in this period (Levelized cost of district heating centre).



**Figure 5-3: Levelized cost of produced heat energy**

Table 5-5 summarizes the levelized costs of various energy options for the base-load and peaking/ backup options. The produced thermal energy from the district heating system is estimated to be 809,421 MWh during these 25 years.

**Table 5-5: Levelized cost of technology options**

| Levelized cost (\$/MWh) | Peaking <sup>a</sup> |              |              | Base-load <sup>a</sup> |              |              |              |
|-------------------------|----------------------|--------------|--------------|------------------------|--------------|--------------|--------------|
|                         | NG                   | NG           | WPGB         | WPG                    | WPPB         | SHR          | GHE          |
| Initial investment      | 13.36                | 1.76         | 7.76         | 10.44                  | 9.36         | 18.63        | 21.54        |
| Operational cost        | 22.87                | 15.62        | 11.32        | 13.22                  | 11.24        | 7.71         | 9.17         |
| <b>Total</b>            | <b>36.23</b>         | <b>17.38</b> | <b>19.08</b> | <b>23.66</b>           | <b>20.60</b> | <b>26.34</b> | <b>30.71</b> |

<sup>a</sup> NG: natural gas boiler, WPGB: wood pellet moving grate burner, WPG: wood pellet gasifier and oxidizer, WPPB: wood pellet powder burner, SHR: sewer heat recovery system, GHE: geothermal heat exchange system.

The levelized cost of heat generated from the natural gas peaking/ backup system is 36.23 CAD/MWh. The operating cost of the peaking/ backup system accounts for 37% of the total cost of heat production. It should be noted that the operating cost of the peaking/ backup system includes the cost of operating staff. Also, common areas of the facility

such as office area, parking, electrical room, etc. are considered in the initial investment requirement of the peaking/ backup system.

As shown in Table 5-5, the cheapest cost of produced heat from the base-load system is due to the natural gas boiler system. The cost of produced heat from the natural gas base-load system is 17.38 CAD/MWh. The O&M cost of the natural gas system is higher than those of renewable options, while the lower initial investment requirement for the natural gas system offsets the effect of the operating costs. The lower initial investment for the natural gas base-load system stems from the fact that the natural gas peaking/ backup system would offer significant savings in the development requirements for the base-load system.

Among renewable options, produced heat from wood pellet systems is cheaper than heat pump systems, which require significantly higher initial investments of all options. A grate burner is the less expensive option of all wood pellet heat conversion systems, mainly due to its lower initial investment. The gasifier- oxidizer system requires higher initial investment of all wood pellet utilizing options and has a higher operating cost due to lower overall efficiency. In terms of the operating cost throughout the life time of the systems, heat pump options are less costly than the wood pellet systems, though their significantly higher initial investment requirements offset the effect of lower operating costs.

### 5.5.1. Carbon tax effect on the economic results

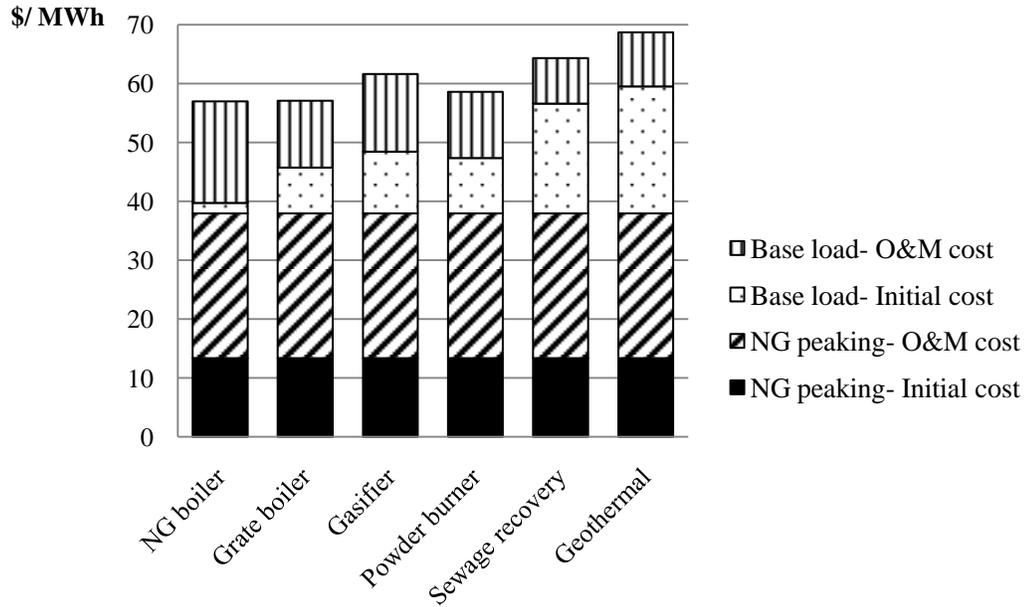
Based on the proposed carbon tax on fossil fuels in British Columbia, the economics of the energy options is expected to change. The proposed rate structure for natural gas is shown in Table 5-6.

**Table 5-6: Carbon tax rate structure for natural gas in BC  
source: (Ministry of small business and revenue, 2008)**

|             | Unit of tax<br>rate | July 1<br>2008 | July 1<br>2009 | July 1<br>2010 | July 1<br>2011 | July 1 2012<br>and after |
|-------------|---------------------|----------------|----------------|----------------|----------------|--------------------------|
| Natural gas | Cents/GJ            | 49.88          | 74.82          | 99.76          | 124.70         | 149.64                   |

Figure 5–4 shows the levilized cost of produced heat by various options when the carbon tax rate structure is applied to the operating costs of the natural gas systems over

the 25-year operation life. As it can be seen, the cost of all options increases because of the increase in operating cost of the peaking/backup system. The economic performance of renewable options, especially wood pellet grate boiler and powder burner are better compared to the natural gas system in this case.



**Figure 5-4: Levelized cost of produced heat when applying carbon tax structure**

As it can be seen in Table 5-7, with the introduction of the tax credit structure, the increase in the total levelized cost of the natural gas peaking/ backup system increases the produced cost of heat in all options. The increased operational cost of the natural gas base-load system upon introduction of carbon taxes reduces the difference in the economic performance of the wood pellet grate boiler and the natural gas boiler further.

**Table 5-7: Levelized cost of technology options after applying carbon tax**

| Levelized cost<br>(\$/MWh) | Peaking <sup>a</sup> |       |       | Base- load <sup>a</sup> |       |       |       |
|----------------------------|----------------------|-------|-------|-------------------------|-------|-------|-------|
|                            | NG                   | NG    | WPGB  | WPG                     | WPPB  | SHR   | GHE   |
| Initial investment         | 13.36                | 1.76  | 7.76  | 10.44                   | 9.36  | 18.63 | 21.54 |
| Operational cost           | 24.61                | 17.23 | 11.32 | 13.22                   | 11.24 | 7.71  | 9.17  |
| Total cost                 | 37.97                | 18.99 | 19.08 | 23.66                   | 20.60 | 26.34 | 30.71 |

<sup>a</sup> NG: natural gas boiler, WPGB: wood pellet moving grate burner, WPG: wood pellet gasifier and oxidizer, WPPB: wood pellet powder burner, SHR: sewer heat recovery system, GHE: geothermal heat exchange system.

## 5.6. Sensitivity analysis

Different fuel prices can influence the operating cost and consequently the best alternative when studying different energy options (Sundberg and Henning, 2002). The sensitivity of the results to changes in 1) fuel prices, 2) initial investment, and 3) efficiency of systems is investigated in this section.

For sensitivity analysis of fuel prices, the natural gas price increase prediction is assumed to follow the lower limit of 95% confidence interval of the predicted regression model. Also, the inflation rate for the electricity price over the 25-year service life is assumed to be at a lower rate of 2% per year rather than 3%. The wood pellets price is also assumed to have 1% inflation rate per year instead of 2% which was originally considered (Trent Berry, 2006).

For sensitivity analysis of initial investment, a 20% increase in initial investment of each option is investigated.

Overall system efficiency of boilers or heat pumps depends on a number of operating and design factors that would influence systems efficiencies. This might be variable from application to application, for example Chau et al. (2009) has used on average 10% higher boiler efficiencies for greenhouse heat producing boilers than what are considered in this analysis. Thus, cost and emissions of different systems are recalculated with considering 10% higher efficiency for different energy systems.

Table 5-8 shows the percentage of change in the present value (2009 base year) cost of different energy options when these factors are altered. By applying any of the above mentioned changes one at a time, the cost of produced heat would become less for the

wood pellet grate boiler compared to that of the natural gas boiler. This shows that the price of produced heat from the natural gas and wood pellet option is comparable for this case. The ranking of the options did not change under any of the considered variations in this sensitivity analysis when they were applied at a same time for all the options.

**Table 5-8: percentage of change in the levelized cost of technology options under varied assumptions**

| Varied item                        | Peaking <sup>a</sup> |      |      | Base- load <sup>a</sup> |      |     |     |
|------------------------------------|----------------------|------|------|-------------------------|------|-----|-----|
|                                    | NG                   | NG   | WPGB | WPG                     | WPPB | SHR | GHE |
| Fuel price alteration              | -4%                  | -8%  | -4%  | -4%                     | -3%  | -2% | -2% |
| 20% increase in initial investment | 7%                   | 2%   | 8%   | 9%                      | 9%   | 14% | 14% |
| System efficiency increase         | -5%                  | -10% | -7%  | -7%                     | -5%  | -2% | -2% |

<sup>a</sup> NG: natural gas boiler, WPGB: wood pellet moving grate burner, WPG: wood pellet gasifier and oxidizer, WPPB: wood pellet powder burner, SHR: sewer heat recovery system, GHE: geothermal heat exchange system.

As the results of sensitivity analyses depicted, 20% increase in the initial investment of natural gas boilers, or 1% less inflation per year for the wood pellet price would make the wood pellet grate boiler option economically preferable to the natural gas boiler for base- load. The ranking of the options did not change when any of the variations in the inputs were considered at the same time for all options.

It is concluded that although natural gas boiler would produce heat at a lower cost, a wood pellet heat producing system (specifically grate boiler) would be well comparable to the natural gas boiler for the considered district heating centre; especially when carbon tax for utilization of natural gas is included in the operating costs. Heat pump options offer lower operating costs compared to all other options, though the overall cost of the produced heat from these technologies are higher due to high initial investment requirements.

## 5.7. Conclusions

In this research chapter, the economic performance of several energy options available to a district heating system in a major urban dwelling (City of Vancouver, BC) was studied. The energy production load in the district heating system was divided between a peaking/backup and a base-load system to provide 40 and 60% of the annual

energy demand, respectively. The considered peaking system was a natural gas boiler. The energy sources considered for the base-load system included natural gas, wood pellet, sewer heat, and ground heat. The technology options considered included: gas-fired boiler for natural gas, moving grate burner, gasifier, powder burner for wood pellet fuel, and heat pumps for sewer and ground heat sources. The economic performance of the energy options was compared against each other using the present value of the initial and O&M costs. Tax savings due to depreciation of major equipment and operating costs of the system were considered in the analysis. The salvage value of building and equipment and resale price of land were considered in the cash flow analysis. The ranking of the technology options in terms of cost of produced heat in the ascending order was as follows: (1) natural gas, (2) wood pellet moving grate burner, (3) wood pellet powder burner, (4) wood pellet gasifier, (5) sewer heat recovery, and (6) geothermal heat exchange. As the results of sensitivity analyses depicted, 20% increase in the initial investment of natural gas boilers, or 1% reduction in wood pellet price inflation would make the wood pellet grate burner option economically preferable to the natural gas boiler for the base-load system. The ranking of other options did not change when input values were changed in the sensitivity analysis. The alternative technology and energy source used for the peaking system should be competitive to the natural gas in terms of cost, fuel security and ease of use. It was concluded that although natural gas boiler would produce heat at a lower cost, a wood pellet grate burner would be well comparable to the natural gas boiler for the considered district heating centre. Heat pump options offer lower operating costs compared to all other options, however, the overall cost of the produced heat from these technologies are significantly higher due to their high initial investment requirements. Moreover, it was concluded in this research that over 43% of the levelized cost of heat production at the considered district heating centre was resulted from high operating cost of the natural gas peaking system (when carbon taxes are introduced). This shows the importance of investigating renewable-based peaking/backup systems to replace the natural gas peaking/backup boiler concept which is the most common practice in BC. The reduced operating cost over the service life of renewable technologies offset the high initial investment requirement of these options

when compared with the fossil fuel technologies. It is therefore more desirable to practically look into alternative options that can replace natural gas for peaking/backup.

## **Chapter 6. Life cycle assessment of base-load heat sources for district heating system options\***

### **6.1. Synopsis**

Increased awareness on environmental burdens of energy consumption has increased the number of governments' stimulus plans towards implementing more efficient energy production systems. The BC Government is anxious to increase the number of renewable energy portfolios in the basket of primary energy sources in the province. Along with other energy intensive sectors, residential and commercial sectors have also been exploring opportunities for more efficient and renewable based energy producing systems in the recent years (Ministry of Energy, Mines and Petroleum Resources, 2009).

The study of the decision making process for the considered district heating centre identified that one of the major environmental organization's concerns regarding the utilization of wood pellets as fuel source was the upstream environmental impacts associated with production and transportation of this fuel source. Especially, it has been argued that such upstream impacts for the wood pellet option would exceed those of other energy options and would offset the GHG reduction advantage of wood pellets as a renewable energy source.

The primary goal of this chapter is to evaluate and compare the performance of four heat source options for the based-load of the considered district heating centre in Vancouver, BC, using the LCA methodology. The ISO framework and guidelines for conducting an LCA study are used in this research. The considered heat sources consist of natural gas, wood pellets, sewer heat, and geothermal heat. This LCA study covers all life stages of the heating centre. The Simapro software v7.0 (<http://www.pre.nl/simapro/default.htm>) is used in this study. Major contributors to the various impact categories from the life cycle of each energy source option are identified.

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\* A version of this chapter is accepted for publication by the International Journal of Life Cycle Assessment. Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, T., Melin, S., Life cycle assessment of base-load heat sources for district heating system options.

## 6.2. Case definition

The district heating centre considered in this chapter is identical with the one explained and studied in previous chapters. The district heating centre consists of a 10 MW<sub>th</sub> peaking/ backup natural gas boiler which provides 40% of the annual energy demand and a 2.5 MW<sub>th</sub> base-load system to operate mostly at full capacity year around to supply 60% of the annual heat demand. Four energy source options of natural gas, wood pellets, sewer heat, and geothermal heat are considered as possible energy options for the base-load system of the district heating centre.

Table 6-1 lists specifications of the base-load system considered in the LCA study.

**Table 6-1: Relevant specifications of the base-load system to the LCA study**

| <b>Base-load system specification</b>                        | <b>Value</b>                     |
|--|----------------------------------|
| Base-load capacity (MW <sub>th</sub> )                       | 2.5                              |
| Service life (years)   | 25                               |
| Produced heat during life time (MWh <sub>th</sub> )          | 486,625                          |
| <b>Heat source alternative (efficiency/ COP<sup>a</sup>)</b> | <b>Technology</b>                |
| Natural gas (82%)  | Low- NO <sub>x</sub> boiler      |
| Wood pellet (75%)  | Moving grate boiler <sup>b</sup> |
| Sewer heat (3.5)   | Sewer heat pump                  |
| Geothermal (2.5)   | Geothermal heat pump             |

<sup>a</sup> Coefficient of performance for heat pump options.

<sup>b</sup> With electro static precipitator for flue gas cleaning.

## 6.3. Goal and scope definition

The infrastructure required for a district heating system includes the energy centre, main grid and auxiliary components, trench works, service pipes, buildings and dwellings components. The energy centre along with the dwelling components such as exchangers are the main contributors to the overall environmental footprints of a district heating system infrastructure, contributing from 40% to more than 90% in all the environmental impact categories (Oliver-Solà et al., 2009). In this study, the energy centre of the district heating infrastructure is the focus of the study.

Those components of the district heating centre that would be the same for all options has been excluded from the study. This exclusion includes: the 10 MW<sub>th</sub> peaking/ backup system, energy centre office and parking area, hot water pump station, and any required

building, equipment, piping, etc. that would not change if alternative options were considered.

The choice of the functional unit for allocating environmental impacts to the heat and/or power generation of an energy plant would significantly affect the life cycle results (Jungmeier et al., 1998). In this study, the functional unit is “1 MWh<sub>th</sub>” of thermal energy produced at the district heating centre by the base-load system.

This LCA study includes: 1) facility construction, 2) fuel/ electricity production cycle and transmission to the facility, 3) facility operation, and 4) dismantling of the facility. Energy and materials used for production of construction materials and equipment as well as energy requirement and wastes from dismantling and recycling processes are incorporated. A rough site specific estimates to evaluate the LCA impact of these phases. Land use, occupation, and disturbance factors were not included in the LCA analysis. Emissions from operating each piece of equipment are calculated and the entire LCA of the manufacturing each piece of equipment, such as LCA of manufacturing trucks or trains used for transportations falls beyond the scope of this study.

The priority in selecting a dataset for life cycle processes in the model was 1) British Columbia specific data, 2) Pacific North West data, 3) North American data, and 4) modified European data base<sup>5</sup> (Frischknecht et al., 2005).

## **6.4. Life cycle inventory**

The energy source options for the district heating base-load system include: 1) natural gas, 2) wood pellet, 3) sewer heat, and 4) geothermal heat. Electricity is the primary energy source for running the heat pump of the sewer heat and geothermal heat exchange systems. Table 6-2 summarizes primary specifications of the energy sources considered for the four energy options.

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<sup>5</sup> Ecoinvent v1.2 is a European database provided in the Simapro software. In this study, Ecoinvent database has been adopted by incorporating North American and case specific inputs into Ecoinvent; exception is the case of major equipment supplied from Europe where the Ecoinvent database is used unchanged.

**Table 6-2: Specifications of primary energy source options for the district heating centre**

| <b>Energy source</b> | <b>Specification</b>              | <b>Value</b>                      |
|----------------------|-----------------------------------|-----------------------------------|
| Electricity*         | Hydro                             | 94.2 (%)                          |
|                      | Natural gas                       | 5.7 (%)                           |
|                      | Others (Petroleum, biomass, etc.) | 0.1 (%)                           |
| Natural gas          | Density                           | 0.7 ( <i>kg/m<sup>3</sup></i> )   |
|                      | Higher heating value              | 10.7 ( <i>kWh/m<sup>3</sup></i> ) |
| Wood pellets         | Density                           | 590 ( <i>kg/m<sup>3</sup></i> )   |
|                      | Higher heating Value              | 5.28 ( <i>kWh/kg</i> )            |
|                      | Moisture content                  | 8 ( <i>wt %</i> )                 |
|                      | Ash content                       | 0.5 ( <i>wt %</i> )               |

\* Primary energy source share for electricity generation

Tables 6-3 to 6-6 show the inputs and datasets used in life cycle inventory of the considered energy options.

**Table 6-3: Inventory dataset of the natural gas option**

| Life stage                    | Process  | Input                          | Value                | Unit                              | Reference   |
|-------------------------------|--|--------------------------------|----------------------|-----------------------------------|---|
| Natural gas production        | Sour natural gas extraction                    | Diesel                         | 0.001                | liter/m <sup>3</sup> NG           | (US LCI database project, 2004a)                              |
|                               |  | Gasoline                       | 0.0005               | liter/m <sup>3</sup> NG           |   |
|                               |  | Residual fuel                  | 0.0006               | liter/m <sup>3</sup> NG           |   |
|                               |  | Natural gas                    | 0.0241               | m <sup>3</sup> /m <sup>3</sup> NG |   |
|                               |  | Electricity                    | 0.81                 | kWh/m <sup>3</sup> NG             |   |
|                               | Natural gas processing                         | Diesel                         | 0.00004              | liter/m <sup>3</sup> NG           |   |
|                               |  | Gasoline                       | 0.00004              | liter/m <sup>3</sup> NG           |   |
|                               |  | Residual fuel                  | 0.00004              | liter/m <sup>3</sup> NG           |   |
|                               |  | Natural gas                    | 0.0255               | m <sup>3</sup> /m <sup>3</sup> NG |   |
|                               |  | Electricity                    | 0.44                 | kWh/m <sup>3</sup> NG             |   |
| Fuel transmission to facility | Natural gas transmission                       | Pipeline transmission          | 102                  | <i>tonne.km</i>                   | Site specific, (Norris, 2004)                                 |
| District heating construction | Construction of base-load system               | 30 MPa Concrete                | 59.8                 | <i>m<sup>3</sup></i>              | Site specific, (Athena Sustainable Materials Institute, 2005) |
|                               |  | Steel rebar                    | 9,390                | <i>kg</i>                         |   |
|                               |  | Galvanized steel               | 1,800                | <i>kg</i>                         |   |
|                               |  | Natural gas boiler             | 2.5                  | <i>MW</i>                         |   |
|                               |  | Ocean transportation of boiler | 1,350                | <i>tonne.km</i>                   |   |
| Facility operation            | Natural gas combustion                         | Natural gas                    | 117.4                | <i>m<sup>3</sup></i>              | Site specific, (Environmental Protection Agency, 2003).       |
| Dismantling                   | Demolition and disposal of reinforced concrete | Concrete disposal              | 148,000              | <i>Kg</i>                         | (Frischknecht et al., 2005) with North American inputs        |
|                               |  | Recycling of metallic pieces   | Steel and iron scrap | 2,800                             |   |

**Table 6-4: Inventory dataset of the wood pellet option**

| Life stage                    | Process  | Input                     | Value                       | Unit                               | Reference              |
|-------------------------------|--|---------------------------|-----------------------------|------------------------------------|------------------------|
| Wood pellet production        | Tree harvesting  | Diesel fuel               | 7.1                         | <i>liter/m<sup>3</sup>wood log</i> | (Sambo, 2002),         |
|                               |  | Sawdust production        | Surface water               | 0.075                              | <i>kg/kg sawdust</i>   |
|                               | Ground water   |                           | 0.113                       | <i>kg/kg sawdust</i>               |                        |
|                               | Electricity  |                           | 0.216                       | <i>MJ/kg sawdust</i>               |                        |
|                               | Propane  |                           | 0.008                       | <i>kJ/kg sawdust</i>               |                        |
|                               | Gasoline   |                           | 0.004                       | <i>MJ/kg sawdust</i>               |                        |
|                               | Diesel   |                           | 0.045                       | <i>MJ/kg sawdust</i>               |                        |
|                               | Sawdust transportation to wood pellet mill                     | Truck transportation      | 27                          | <i>km</i>                          | (Magelli et al., 2009) |
|                               | Pelletization  | Electricity               | 403.8                       | <i>MJ/tonne wood pellet</i>        | (Mani, 2005)           |
|                               |  | Fuel for drying (Sawdust) | 3168                        | <i>MJ/tonne wood pellet</i>        |                        |
| Diesel                        |  | 205.73                    | <i>MJ/tonne wood pellet</i> |                                    |                        |
| Fuel transmission to facility | Transportation of wood pellet to Vancouver storage site        | Truck transportation      | 25                          | <i>km</i>                          | (Magelli et al., 2009) |
|                               |  | Train transportation      | 781                         | <i>km</i>                          |                        |
|                               | Wood pellet handling at storage site                           | Electricity               | 11.12                       | <i>MJ/tonne wood pellet</i>        | (Pa, 2009)             |
|                               | Transportation of wood pellet from storage to district heating | Truck transportation      | 11                          | <i>km</i>                          | Site specific          |

**Table 6-4: Inventory dataset of the wood pellet option (continued)**

| Life stage                    | Process  | Input                          | Value   | Unit                            | Reference   |
|-------------------------------|--|--------------------------------|---------|---------------------------------|---|
| District heating construction | Construction of base-load system               | 30 <i>MPa</i> Concrete         | 101.5   | <i>m</i> <sup>3</sup>           | Site specific, (Athena Sustainable Materials Institute, 2005) |
|                               |  | Steel rebar                    | 15,900  | <i>kg</i>                       | Site specific, (US LCI database project, 2004b)               |
|                               |  | Galvanized steel               | 2,240   | <i>kg</i>                       |   |
|                               | Grate wood boiler acquisition                  | Grate wood boiler              | 2.5     | <i>MW</i>                       | (Frischknecht et al., 2005)                                   |
| Facility operation            | Wood pellet combustion                         | Ocean transportation of boiler | 15,490  | <i>tonne.km</i>                 | Site specific, (Norris, 2004)                                 |
|                               |  | Wood pellets                   | 0.253   | <i>tonne/MWh</i> heat generated | Site specific, (Environmental Protection Agency, 2003).       |
| Dismantling                   | Demolition and disposal of reinforced concrete | Concrete disposal              | 252,000 | <i>kg</i>                       | Ecoinvent with North American inputs                          |
|                               | Recycling of metallic pieces                   | Steel and iron scrap           | 4,000   | <i>kg</i>                       |   |

**Table 6-5: Inventory dataset of the sewer heat option**

| Life stage                    | Process  | Input                | Value    | Unit                          | Reference   |
|-------------------------------|--|----------------------|----------|-------------------------------|---|
| Electricity production        | Electricity generation                         | Hydro                | 94.2     | %                             | (Gagnon et al., 2002), (Koch, 2000)<br>(Norris, 2004)<br>(Norris, 2004) |
|                               |  | Natural gas          | 5.7      | %                             |   |
|                               |  | Others               | 0.1      | %                             |   |
| Electricity transmission      | Long distance transmission                     | Electricity loss     | 1.8      | %                             | (Frischknecht et al., 2005)   |
| District heating construction | Construction of sewage pump station            | 30 MPa Concrete      | 232.5    | m <sup>3</sup>                | Site specific, Athena sustainable materials institute, 2005)            |
|                               |  | Steel rebar          | 36,502   | kg                            | Site specific, (US LCI database project, 2004b)                         |
|                               |  | Galvanized steel     | 41,174   | kg                            |   |
|                               | Construction of exchange house                 | 30 MPa Concrete      | 115      | m <sup>3</sup>                | Site specific, Athena Sustainable Materials Institute, 2005)            |
|                               |  | Steel rebar          | 18,100   | kg                            | Site specific, (US LCI database project, 2004b)                         |
|                               |  | Galvanized steel     | 6,140    | kg                            |   |
|                               | Heat pump                                      | Heat pump            | 2.5      | MW                            | (Frischknecht et al., 2005)   |
| Ocean transportation          |  | 20,350               | tonne.km | Site specific, (Norris, 2004) |   |
| Facility operation            | Electricity for heat pumps                     | Electricity          | 0.286    | MWh/MWh <sub>h</sub>          | Site specific   |
|                               | Electricity for sewage pumps                   | Electricity          | 8.33     | KWh/MWh <sub>h</sub>          | Site specific   |
| Dismantling                   | Demolition and disposal of reinforced concrete | Concrete disposal    | 862,000  | kg                            | Ecoinvent with North American inputs                                    |
|                               | Recycling of metallic pieces                   | Steel and iron scrap | 47,315   | kg                            |   |

**Table 6-6: Inventory dataset of the geothermal option**

| Life stage                    | Process  | Input   | Value           | Unit         | Reference                                       |
|-------------------------------|--|---|-----------------|--------------|---|
| Electricity production        | Electricity generation                         | Hydro   | 94.2            | %            | (Gagnon et al., 2002), (Koch, 2000)             |
|                               |  | Natural gas                                   | 5.7             | %            | (Norris, 2004)                                  |
|                               |  | Others  | 0.1             | %            | (Norris, 2004)                                  |
| Electricity transmission      | Long distance transmission                     | Electricity loss                              | 1.8             | %            | (Frischknecht et al., 2005)                     |
| District heating construction | Geothermal trench development                  | Infrastructure for geothermal vertical trench |                 |              | Ecoinvent with North American inputs            |
|                               |  | Construction of exchange house                | 30 MPa Concrete | 90           | m <sup>3</sup>                                  |
|                               | Heat pump                                      | Steel rebar                                   | 14,150          | kg           | Site specific, (US LCI database project, 2004b) |
|                               |  | Galvanized steel                              | 4,800           | kg           |   |
|                               |  | Heat pump                                     | Heat pump       | 2.5          | MW  |
|                               |  | Ocean transportation                          | 20,350          | tonne.km     | Site specific, (Norris, 2004)                   |
| Facility operation            | Electricity for heat pumps                     | Electricity                                   | 0.4             | MWh/MWh heat | Site specific                                   |
| Dismantling                   | Demolition and disposal of reinforced concrete | Concrete disposal                             | 285,000         | kg           | Ecoinvent with North American inputs            |
|                               | Recycling of metallic pieces                   | Steel and iron scrap                          | 6,140           | kg           |   |

## **6.4.1. Fuel production**

### **6.4.1.1. Electricity**

Electricity is an important input for processes included in the LCA study in addition to providing the primary energy source for sewage and geothermal heat pumps. The inventory associated with electricity is dependent on the production profile of each region. The electricity generation profile in British Columbia has been: 94.2% of hydro generated electricity (14.1% run-of-river hydropower, 80.1% reservoir hydro power plant), 5.7% natural gas power plants, and 0.1% from other sources (petroleum sources, biomass) (St. Lawrence, 2007). Emission factors considered in the inventory of hydro power include CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> obtained from Gagnon et al. (2002) and particulate emissions from Koch (2000). CO<sub>2</sub> emissions from hydro power generation are from the flooded biomass and decay (Gagnon et al., 2002). The emission factors for natural gas and other sources of generated electricity are obtained from Franklin database (Norris, 2004).

### **6.4.1.2. Natural gas**

The life cycle of natural gas production and transmission to the district heating base-load system, starts with natural gas extraction. Natural gas is commonly co-extracted with crude oil and due to its hydrogen sulfide content is referred to as “sour” gas. In order to obtain marketable natural gas, processing is required to remove heavier hydrocarbons of ethane, butane, propane (liquefied petroleum gases), water vapor, carbon dioxide, nitrogen (to increase heating value), and hydrogen sulfide (“sweetening”). Natural gas processing is an energy consuming operation which also releases air borne emissions of fugitive methane, sulfur dioxide, benzene, toluene, ethylbenzene, and xylene (US LCI database project, 2004a). Since natural gas processing plants are located in the proximity of the extraction sites, it is assumed that transportation between extraction and processing is negligible.

### **6.4.1.3. Wood pellets**

British Columbia produced over 1.3 million tonnes of wood pellets in 2009; over 90% of which was exported overseas for heat and power production purposes (Government of

B.C., 2010). Wood pellets are categorized as a bio-energy source with zero net CO<sub>2</sub> emission during combustion.

Currently in BC, wood pellets are produced from stem-wood sawdust received from sawmills. Therefore, the life cycle of wood pellets starts from harvesting trees for lumber production. The average energy consumption for harvesting activities in Western Canada region is 7.1 liters of diesel fuel per m<sup>3</sup> of harvested wood (Sambo, 2002). This average includes planning and layout development, road construction, logging, hauling, camping, silviculture, and also average log transportation to the sawmill. The harvesting regime in this region has been 17% thinning and 83% clear cut (Niemann, 2006).

The water and energy consumption and air and soil emissions for sawmill operation in the Pacific Northwest region were obtained from (Milota et al., 2005) and is allocated on a mass basis to the sawdust portion of sawmill byproducts which is used in wood pellet production. Sawmill operations on harvested logs would on average yield 8% bark, 1% hogfuel, 7% sawdust, 27% chips, and 57% lumber on a mass basis. The average densities of logs and sawdust are 500 kg/m<sup>3</sup> and 200 kg/m<sup>3</sup> respectively.

In BC, sawdust is transported, on average, a distance of 27 km by trucks to wood pellet producing plants (Magelli et al., 2009) to be used as: 1) wood pellet raw material (1.56 tonnes sawdust/1 tonne wood pellet) and 2) energy source for the drying phase of wood pellet production (267 kg sawdust/1 tonne wood pellet) (Mani, 2005). The amount of electricity and diesel fuel consumption in a wood pellet plant are also obtained from (Mani, 2005). Emission factors for sawdust combustion at wood pellet plant is estimated based on EPA emission factors for wet wood residue combustion (Environmental Protection Agency, 2003).

A key assumption in developing the emission inventory of biomass combustion is that the net CO<sub>2</sub> emissions resulting from sawdust or wood pellets combustion is zero (Johnson, 2009).

#### **6.4.2. Energy source transmission**

Transmission of electricity to the facility has been incorporated in the LCA inventory terms of electricity loss. The average electricity loss due to high voltage long-distance transmission was considered to be 30 Wh per MWh.km (Frischknecht et al., 2005). The weighted average long distance electricity transmission is 750 km based on distances from major electricity generation sites in BC which are located at Peace Region (34% electricity generation contribution, 1200 km), Columbia Region (31% electricity generation contribution, 600 km), and the Interior and Coastal Regions (35%, various locations from 100 to 1000 km) (Shabani, 2009). Franklin database is used for pipeline transmission of natural gas from an average distanced natural gas inlet station located at Fort St. John, BC, to the district heating system in Vancouver, BC, which is 1200 km.

GHGenius 3.16c developed by Natural Resources Canada for life cycle assessment of transportation fuels (<http://www.ghgenius.ca/>) is used to estimate emissions from heavy duty diesel or gasoline engines, truck and train transportations. The average diesel truck fuel consumption has been corrected to 66 liters per 100 kilometers (Ressaire, 2006); this average represents truck fuel consumption with and without a 25 tonne payload in a tri-axle semi trailer normally used for such type of transportation.

Transportation of wood pellets to the district heating centre for final use includes a series of truck and train transportation and storage. After production, wood pellets are transported to railhead for an average distance of 25 km and then transported over an average distance of 781 km via rail to a port in Vancouver, BC (Magelli et al., 2009). Wood pellet truck transportation is considered as a two-way trip: one way loaded and one way commuting back unloaded. Electricity and fuel consumed at the Vancouver port for unloading, storage, and then loading of wood pellets are obtained from Pa (2009) who surveyed Wood pellet Association of Canada. Wood pellets are trucked to the energy centre over a distance of 11 km for combustion in a grate boiler for heat generation purpose.

### **6.4.3. District heating centre construction**

The structure of the district heating centre is made from reinforced concrete. Emissions and recourse inventories for 30 MPa structural concrete type, which is a common type of structure for building constructions in Vancouver, are obtained from (Athena Sustainable Materials Institute, 2005). The amount of steel rebar (US LCI Database Project, 2004b) on a volume basis is 2% of concrete volume and the density of steel is 7,850 kg/m<sup>3</sup>. The energy consumption during facility construction is not included in the inventory. The inventory of steel pipes required for the boiler and exchange houses have been developed based on the US LCI information for galvanized steel sheet production (US LCI database project, 2004b) and the North American inputs incorporated in Ecoinvent database has been used for drawing process of pipe production. The required pieces of equipment for different options, such as natural gas boiler, wood pellet boiler, heat pumps, and exchangers, were assumed to be procured in Europe, therefore the Ecoinvent database was used to develop the inventory of the equipment. The inventory also includes ocean shipment of the equipment from Europe to Vancouver, BC.

The inventory of wood boiler procured from Europe includes the required auxiliary equipment such as chimney, storage silo, automatic fuel supply system, and automatic control. Ocean transportation of equipment is also included for an average distance of 7,400 km between Europe and BC, Canada. The inventory of electro static precipitator system on wood boiler is not included.

For the geothermal option, the North American incorporated Ecoinvent database has been used for the drilling and construction activity of a 150 m deep geothermal vertical loop configuration. Major components of the geothermal exchange system are the heat exchanger, heat pump, geothermal wells (vertical trench), and required interconnecting piping between the wells and heat exchangers.

The specifications of the required sewage pump station to redirect, pre-treat and make the sewage useable in the exchangers are site specific. Major components of the sewage heat recovery system include heat exchanger, heat pump, interconnecting piping between

treatment equipment and heat exchangers, cooling tower evaporator, and sewage pretreatment unit, which consists of auto cleaning screens, booster pumps, backwash pits, and transfer pumps. Inventory of the mechanical equipment for sewage pump station including screens and pumps were not available to include in the model. Electricity and water used during the operation of the sewage pump station are also included in the sewage pump station inventory.

#### **6.4.4. District heating centre operation**

The amount of energy used (fuel and electricity) during the operation of the district heating system and emissions generated from fuel combustion were considered in the LCA analysis. Electricity consumption to run heat pumps of the sewer heat recovery and geothermal options has been calculated based on 3.5 and 2.5 coefficient of performance (COP) for the systems, respectively. The amount of natural gas burned in the boiler to produce 1 MWh thermal energy based on 82% boiler efficiency and 10.7 kWh/m<sup>3</sup> natural gas energy density would be 118.7 m<sup>3</sup>. The combustion emissions of a low NO<sub>x</sub> natural gas boiler have been obtained from EPA AP-42 (Environmental Protection Agency, 2003). The amount of wood pellets required to produce 1 MWh thermal energy based on 75% boiler efficiency and wood pellets energy density of 5.28 kWh/kg would be 253 kg. The combustion emissions for burning dry wood in wood boiler equipped with an electro static precipitator has been obtained from EPA AP-42 (Environmental Protection Agency, 2003). The emission levels reported in EPA AP-42 for composition of particulates such as alkali and heavy metals or dioxin and furans have been reduced by a factor of 95% as a result of ESP cleaning. The original levels reported in EPA AP-42 do not incorporate flue gas cleaning reduction measures.

#### **6.4.5. Dismantling**

The dismantling process is assumed to occur after 25-year service life of the district heating centre. The inventory of dismantling process for various heat source options have been developed based on the North American inputs incorporated into the Ecoinvent database. It is assumed that construction wastes are dumped in a landfill and metals such as steel pipes are recycled.

## 6.5.Life cycle impact assessment and discussion

The environmental impacts of all consumed resources and resulting emissions are assessed in terms of midpoint categories and endpoint damage indicators using IMPACT 2002+ v2.1 (Jolliet et al., 2003). The IMPACT 2002+ method as suggested by the International Standard Organization (ISO 14042, 2000) benefits from both classical impact assessment methods, which consider the so-called midpoint categories, and the damage oriented methods, which report the endpoint indicators. Twelve out of fourteen midpoint impact categories and four endpoint damage categories and their equivalent indicators which IMPACT 2002+ reflect upon are considered in this study. Land occupation and ionizing radiation midpoint categories were not included in the impact assessment since the associated inventory of these midpoint categories have not been developed in this study. The midpoint categories of each heat source option considered for the district heating centre can be seen in Table 6-7.

**Table 6-7: Midpoint categories of various heat source options per MWh thermal energy produced at the district heating centre**

| Midpoint category                     | Unit                  | Natural gas | Wood pellets | Sewer    | Geothermal |
|---------------------------------------|-----------------------|-------------|--------------|----------|------------|
| Carcinogens <sup>a</sup>              | kg $C_2H_3Cl$         | 0.384       | 0.278        | 0.0808   | 0.0288     |
| Non-Carcinogens <sup>a</sup>          | kg $C_2H_3Cl$         | 5.76        | 0.219        | 0.267    | 0.359      |
| Respiratory inorganics                | $kg_{eq} PM_{2.5}$    | 0.256       | 0.292        | 0.0165   | 0.0222     |
| Respiratory organics                  | $kg_{eq} ethylene$    | 0.0345      | 0.0223       | 0.000102 | 0.000102   |
| Ozone layer depletion                 | $kg_{eq} CFC-11$      | 1.25E-08    | 0.0000187    | 0.00122  | 0.00183    |
| Aquatic ecotoxicity                   | $kg_{eq} TEG^b$ water | 36000       | 515          | 1530     | 2390       |
| Terrestrial ecotoxicity               | $kg_{eq} TEG^b$ soil  | 7.45        | 43.9         | 15.2     | 24.8       |
| Terrestrial acid./nutri. <sup>c</sup> | $kg_{eq} SO_2$        | 4.68        | 7.07         | 0.44     | 0.59       |
| Aquatic acidification                 | $kg_{eq} SO_2$        | 2.72        | 0.998        | 0.149    | 0.201      |
| Aquatic eutrophication                | $kg_{eq} PO_4^{3-}$   | 0.00258     | 0.000101     | 0.000151 | 0.000227   |
| Global warming                        | $kg_{eq} CO_2$        | 240         | 39.4         | 15.8     | 24.6       |
| Non-renewable energy                  | $MJ$ primary          | 4390        | 208          | 21.1     | 29.8       |
| Mineral extraction                    | $kg_{eq} iron$        | 0.0271      | 0.0275       | 0.0501   | 0.0528     |

<sup>a</sup> Human toxicity effect

<sup>b</sup> TriEthylene Glycol

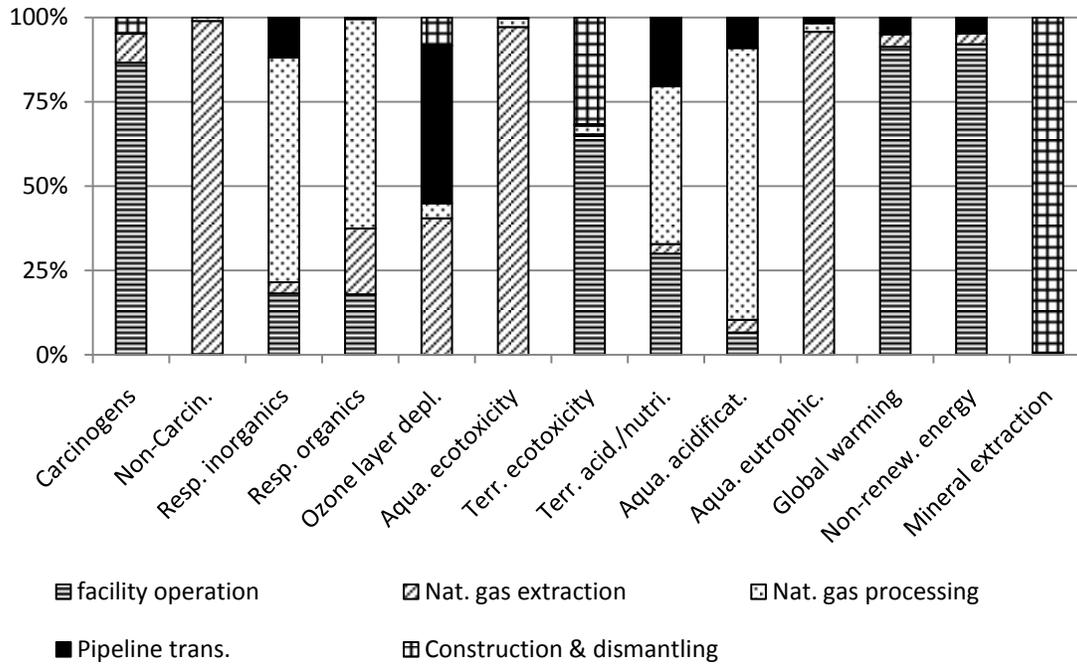
<sup>c</sup> Acidification/ nitrification

The midpoint category values are not readily interpretable to environmental impacts; rather they should be considered as a comparative tool for environmental performance of alternative options. The midpoint categories can be classified into three classes based on their impact range: 1) local impacts such as human toxicity and respiratory effects that are related to human health effects, 2) regional impacts such as ozone layer depletion, aquatic and terrestrial impacts, and 3) global impacts including global warming, non-renewable energy consumption, and mineral extraction categories.

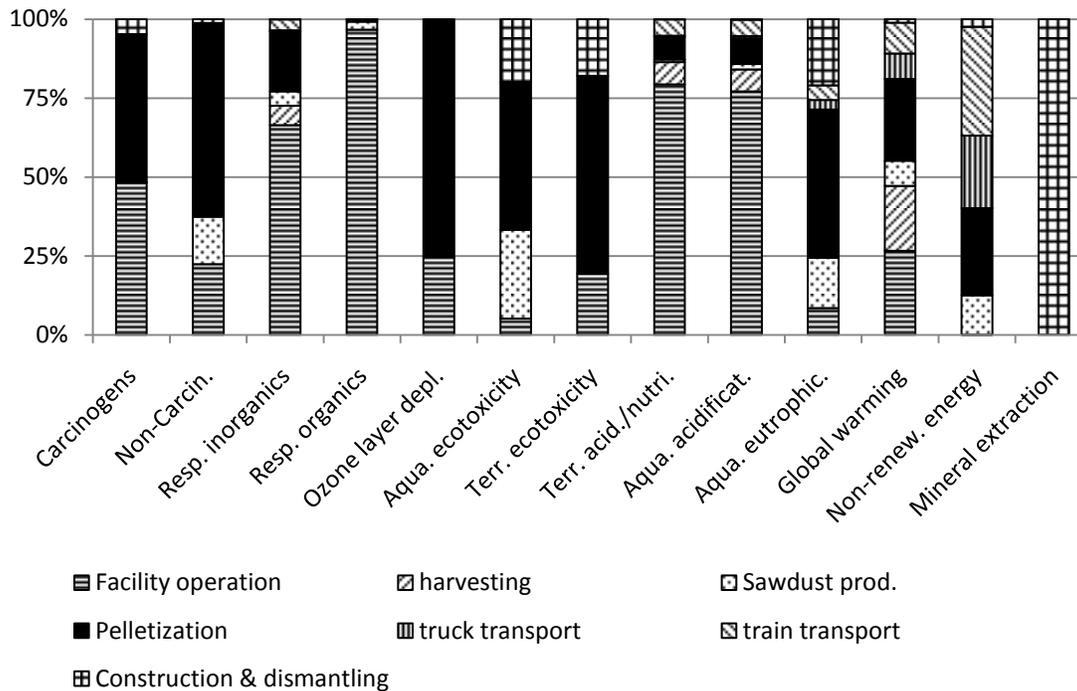
The potential risks associated with the local midpoint categories that affect human health are very much dependent to the level and duration of human exposure to the associated toxic substances. For example, direct human occupational exposure to vinyl chloride has very high risks of angiosarcoma of the liver, but the risk level reduces to negligible when considering the general public's risk of angiosarcoma due to escaping vinyl chloride into the environment from plants carrying this substance in the past (Doll, 1988). Thus, the risk of these midpoint categories for each option, despite the overall value, should be identified based on the upstream inventory of main contributors and whether the risk of human exposure could be high or not. Emissions from a local facility can be seen as high and long term human exposure risk for the people living in the vicinity of the facility.

Comparison of LCA midpoint categories of the four energy options show that a single energy source option that outperforms other options with regards to all the midpoint categories cannot be identified. When comparing to the renewable options, natural gas option results in higher impacts in global warming, non-renewable energy consumption, carcinogens and non-carcinogens, respiratory organics, and aquatic ecotoxicity, acidification, and eutrophication.

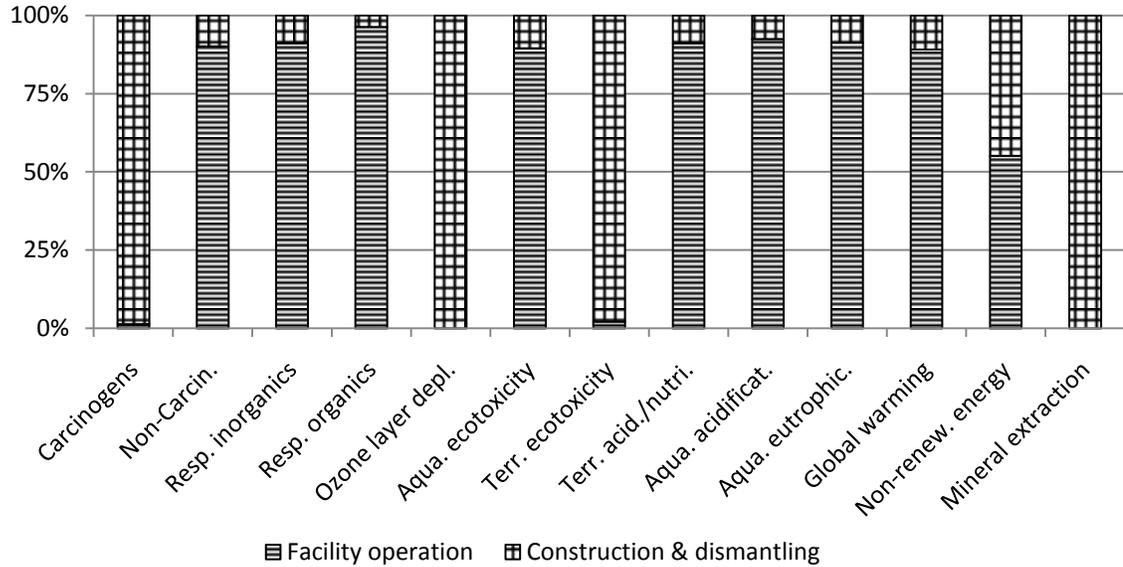
Figures 6-1 to 6-4 represent the contribution of various phases of fuel preparation and transportation/ transmission, facility operation, and facility construction and dismantling for each heat source option.



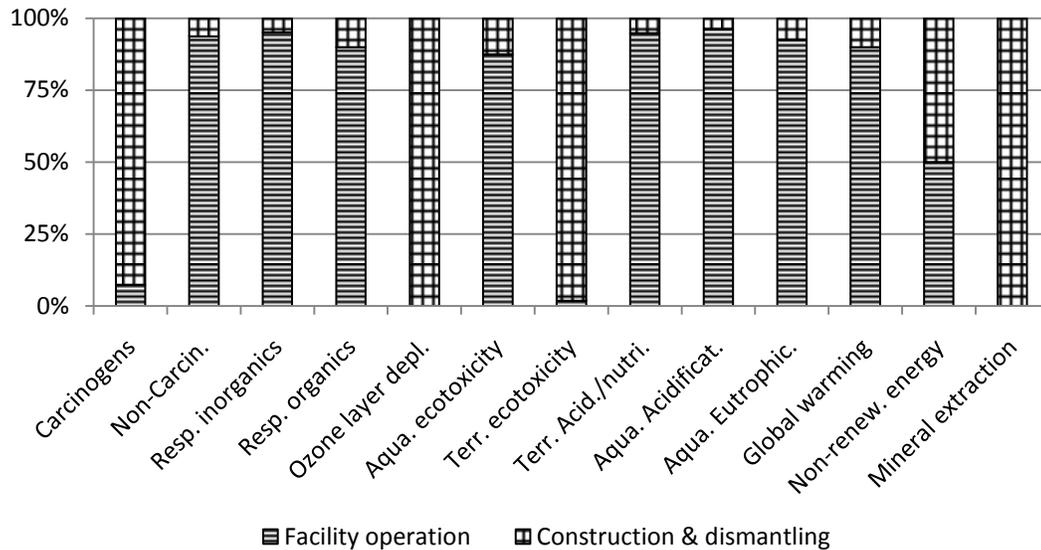
**Figure 6-1: Percent contribution of life cycle stages on midpoint effects – Natural gas option**



**Figure 6-2: Percent contribution of life cycle stages on midpoint effects – Wood pellets option**



**Figure 6-3: Percent contribution of life cycle stages on midpoint effects – Sewer heat option**



**Figure 6-4: Percent contribution of life cycle stages on midpoint effects – Geothermal heat option**

As it can be seen in Figure 6-1, facility operation, i.e. midpoint effects due to emissions from natural gas combustion, has remarkable contribution to midpoint categories of carcinogens, terrestrial ecotoxicity, acidification and nutrification, global warming, and non-renewable energy consumption. The carcinogenic effect of the natural gas option is mostly due to molybdenum and VOC emissions found in the flue gas of

natural gas combustion during facility operation. Trace elements of copper, cadmium, chromium, and aluminum found in natural gas flue gas combustion majorly account for facility operation contribution to the terrestrial ecotoxicity of this option. The natural gas extraction phase contributes significantly to non-carcinogens, ozone layer depletion, aquatic ecotoxicity, and aquatic eutrophication categories of the natural gas option. Release of tetrachloromethane during natural gas extraction and also long distance pipeline transmission stages result in most of the ozone layer depleting effect of this process. Natural gas extraction results in waterborne emissions of aluminum and barium (US LCI database project, 2004a) which has very high aquatic ecotoxicity effect. Also, the Chemical Oxygen Demand (COD) during natural gas extraction is a major contributor to the aquatic eutrophication impact of the natural gas option. Natural gas processing has higher impacts on the two respiratory categories: terrestrial acidification/ nitrification, and aquatic acidification. The respiratory problems associated with natural gas processing are again considered as low human exposure risk due to remote location of natural gas processing stations. Sulphur dioxide emission during natural gas processing phase is the main contributor for terrestrial acidification/ nitrification and aquatic acidification impacts of the natural gas option. Facility construction and dismantling of the natural gas option is not only the single contributor to the mineral extraction category but also results in terrestrial acidification/nitrification effect; the latter effect from construction and dismantling of the natural gas facility are due to aluminum, copper, chromium, and iron used in the manufacturing of the pipes, natural gas boiler, and pipe line transmission.

Figure 6–2 depicts contribution of various life cycle stages of the wood pellets option. In comparison with other energy options, the wood pellets option has higher impacts with regard to respiratory of inorganics and terrestrial ecotoxicity, acidification, and nitrification effects. Emissions from wood pellets combustion during facility operation is the major contributor to the respiratory effects. The major contributors to the respiratory inorganics category were particulate emissions and nitrogen oxides from wood pellets combustion. Copper emissions to soil and to a lesser degree to the atmosphere are considered the most toxic factors in the aquatic and terrestrial ecotoxicity midpoint categories. In the case of the wood pellets option entrainment of copper element in the flue gas and especially bottom ash during sawdust production, pelletization, and facility

operation account for majority of the aquatic ecotoxicity effect of this option. Trace elements of heavy metal found in the flue gas and ash of combusted wood during the pelletization process are the most important contributors to the terrestrial ecotoxicity impact of utilizing wood pellets. It is assumed here that pellet producing facilities do not implement high efficiency flue gas cleaning technologies such as ESPs or baghouses for the sawdust combustion used for the drying phase. It should also be noted that the emissions levels reported here for particulate emissions for the wood pellet option does not suggest whether or not the levels of particulate emissions and dioxin and furans exceed the regulatory limits of the region. The measured particulate emission levels from wood pellet combustion at a district heating facility with the relatively same technology and capacity as considered in this study were in the 55-100 mg/m<sup>3</sup> (at 20°C, 101.325 kPa, dry gas, and 8% O<sub>2</sub>) range (Johansson et al. 2004). With the installation of an ESP system with collection efficiency above 90% (Hasler and Nussbaumer 1999), this emission level will be well below the regulatory limits of 18 mg/m<sup>3</sup> (at 20°C, 101.325 kPa, dry gas, and 8% O<sub>2</sub>) in Vancouver, BC (Metro Vancouver 2008).

As it can be seen in Figure 6–3 and Figure 6–4, the contribution of various life stages of the sewer heat recovery and geothermal options to the midpoint categories show relatively the same pattern. The geothermal and sewer heat recovery options have the highest impact levels on ozone layer depletion and require higher mineral extraction compared to other alternatives. The facility construction and dismantling phase for both heat pump options is the major contributor to both the ozone layer depletion and mineral extraction effects. The working fluid compound of HCFC as in Li et al. (2002) used in the heat pump systems is the major contributor to ozone depletion effect of sewer and geothermal options. Facility operation for both options which include electricity generation and transmission to the facility is responsible for major impacts on non-carcinogens, respiratory, aquatic ecotoxicity, acidification, and eutrophication, terrestrial acidification/nitrification, global warming and non-renewable energy consumption categories. These effects from both options are mainly resulted from the fossil fuel generated portion of the electricity utilized by the heat pumps.

Among renewable options, the global warming effect of the heat pump of sewage and geothermal options that operate based on low carbon electricity is less than that of the wood pellet option. This result is very dependent on the efficiency (COP) of the utilized systems and also electricity generation profile of the region. In the current situation in BC, majority of electricity is low carbon hydro generated. In other words, if the share of fossil fuel generated electricity increases in the electricity generation profile of the region, this result may not be valid anymore. Global warming effect of wood pellet production will also be higher if non-renewable energy sources such as natural gas be used for heat generation during pelletization process.

The results of this study also show that vast primary resource depletion and global warming effects are not the only environmental impacts associated with utilization of natural gas as the heat source, but also human toxicity effects due to natural gas combustion during facility operation and ecosystem quality degradation (especially aquatic ecosystems) at natural gas processing and extraction sites are major environmental issue associated with this option. Mitigation of natural gas extraction effects on the regional ecosystem through alternative processes can be studied further.

## **6.6. Conclusions**

In this study, the life cycle environmental burdens of several energy options available to a district heating system in Vancouver, BC were studied. The energy production load in the district heating system was divided between a peaking/ backup and a base-load system to provide 40% and 60% of the annual energy demand, respectively. The considered peaking system was a natural gas boiler. The energy sources considered for the base-load system included natural gas, wood pellet, sewer heat and ground heat. The LCA analysis considered all the life stages of the base-load system: facility construction, fuel/ electricity production phase, facility operation, and facility dismantling. The IMPACT 2002+ method was used for impact assessment and midpoint impact categories were reported. The results showed that none of the energy options outperformed other alternatives considering all the midpoint impact categories. It was shown that utilizing wood pellets option instead of natural gas would result in reduction of more than 200 kg<sub>eq-co2</sub> per MWh of heat produced at the district heating centre. The results for sewage

heat and geothermal heat options are dependent on the efficiency (COP) of the systems and also electricity generation profile of the region. In the current situation in BC, most of the generated electricity is low carbon hydro electricity. In other words, if the share of fossil fuel increases in the electricity generation profile of the region, the results would change. Global warming effect of wood pellet production will also be higher if non-renewable energy sources such as natural gas be used for heat generation during pelletization process. The results of this study also show that vast primary resource depletion and global warming effects are not the only environmental impacts associated with utilization of natural gas as the heat source, but also human toxicity effects due to natural gas combustion during facility operation and ecosystem quality degradation (especially aquatic ecosystems) at natural gas processing and extraction sites are major environmental issue associated with this option. Mitigation of natural gas extraction effects on the regional ecosystem through alternative processes can be studied further.

## **Chapter 7. Conclusions, limitations, and future research directions**

### **7.1. Conclusions**

This thesis examined the hypothesis that “the wood pellet is a competitive primary energy source option for generating district heat in Vancouver, BC”. In order to address the hypothesis, the decision making process for selecting the energy source of a major district heating project in Vancouver, BC, was investigated. Alternative energy sources for the district heating centre included wood pellets, natural gas, sewer heat, and geothermal heat.

An analysis of the decision making process for selecting district heating energy sources for the considered case was carried out in order to identify the major issues considered by various stakeholder groups for using wood pellets in district heating in Vancouver, BC. Moreover, a multi criteria decision making method was used in the observed decision making process to investigate how the stakeholders’ perceptions about energy source options for the district heating system affected the decision making process outcome. It was shown that in addition to the technical and economic criteria, environmental and social acceptability are significant criteria in selecting the wood pellet as a primary heat source option. The stakeholders were concerned with the global warming impacts associated with production and transportation of the wood pellet to the district heating centre, as well as particulate matter emissions from wood pellet combustion at the facility. Multi criteria analyses confirm that if concerns about local impacts of wood pellet utilization at the facility are left unanswered, the wood pellet option will be screened out during the decision making process.

Based on the results of the decision making study, three objectives are sought in order to reflect on the “competitiveness” of wood pellets as the primary fuel source for district heating in Vancouver. These objectives were to study: (a) particle emissions formation and levels from district heating systems utilizing wood pellets as fuel (Chapter 4), (b) techno-economic performance of wood pellet technology options for district heat

production at the facility (Chapter 5), and (c) upstream and life-cycle environmental impacts of producing district heat from wood pellets (Chapter 6). Investigation of these objectives yields the general conclusions as follows:

In Chapter 4, it is concluded that the formation and levels of particulate emissions from wood biomass combustion is influenced by three factors: wood fuel property, combustion condition, and use of flue gas cleaning equipment. Wood fuel combustion forms two distinct modes of particulate sizes in sub-micron ( $<1 \mu\text{m}$ ) and super-micron ( $>1 \mu\text{m}$ ) ranges. It was concluded that wood fuel quality, which is defined by both physical properties and chemical composition, has a direct impact on the formation of submicron as well as super-micron particle emissions. Utilizing high quality wood fuel is the primary consideration in order to assure limited particulate emissions especially in the submicron particle size range and dioxins and furans emissions, which are regarded as having high health risk implications. Combustion of uncontaminated natural wood in modern district heating plants with flue gas cleaning systems will produce dioxin emission levels well below the health risk limit of  $0.1 \text{ ng I} - \text{TEQ}/\text{m}^3$ .

High quality solid wood fuel is produced from natural stem wood, free of impurities such as preservatives, glue, paint, salt, sand, and has low moisture content. Wood fuel from non-stem wood, such as bark, contains high ash and alkali and heavy metal content, which results in submicron toxic particle emissions in the wood combustion flue gas. Therefore, combustion of low quality wood fuels such as wet logging residues, demolition wood, and bark is not recommended for district heating centres located in populated areas due to the possibility of uncontrolled toxic vapors being released in the flue gas during combustion.

Among the various types of available wood fuel, direct combustion of wood pellets and briquettes produced from stem wood generates the least amount of PM emissions downstream of cyclone abatement technology ( $50\text{-}100 \text{ mg}/\text{m}^3$ -  $20^\circ\text{C}$ ,  $101.325 \text{ kPa}$ , dry gas and  $8\% \text{ O}_2$ ). Therefore, efficient gas cleaning systems, such as ESPs or baghouses should be implemented downstream of the cyclone system in wood burning district heating systems in order to meet the stringent particulate regulatory emissions limit

introduced in Vancouver, BC. Implementation of efficient abatement systems with more than 90% collection efficiency, will drop the particulate emissions to less than 10 mg/m<sup>3</sup> (20°C, 101.325 kPa, dry gas and 8% O<sub>2</sub>) which is well below the Vancouver regulatory limit. Particulate emission levels from combustion of dry wood fuel produced from natural, uncontaminated stem wood, such as dry sawdust, dry wood chips and shavings, are slightly higher than those from wood pellets and briquettes under comparable combustion and flue gas cleaning condition.

In Chapter 5, which addresses the economic performance of wood pellet technologies, three technology options for producing heat from wood pellets (moving grate boiler, gasification system, and powder burner) were compared to those of natural gas, sewer heat recovery, and geothermal heat exchange options for the base-load district heat generation. The economic ranking of the technology options in terms of the cost of produced heat per MWh of base-load heat produced in ascending order was as follows: 1) natural gas (CAD 17.38), 2) wood pellet moving grate burner (CAD 19.08), 3) wood pellet powder burner (CAD 20.60), 4) wood pellet gasifier (CAD 23.66), 5) sewer heat recovery (CAD 26.34), and 6) geothermal heat exchange (CAD 30.71). It is concluded that although the natural gas boiler would produce heat at a lower cost, the cost of heat production with the wood pellet grate boiler system would be comparable to the natural gas boiler for the considered district heating centre. This is especially so when the carbon tax for utilization of natural gas is included in the operating costs, since the base-load heat production cost for the wood pellet grate boiler (CAD 19.08) is fairly comparable to the natural gas boiler (CAD 18.99). A sensitivity analysis showed that a 20% increase in the initial investment of natural gas boilers, or 1% less inflation per year for the wood pellets price, would make the wood pellet grate boiler option economically preferable to the natural gas boiler for base-load. Heat pump options offer lower operating costs compared to that of wood pellets options, though the overall cost of the produced heat from heat pump options is higher due to high initial investment requirements for these systems.

In Chapter 6, life-cycle environmental impacts of utilizing the wood pellet option at the district heating centre is compared to those of the natural gas, sewer heat recovery,

and geothermal heat exchange options. Impact categories considered in the life cycle analysis were human health impacts (carcinogenic, non-carcinogens, respiratory organics, and respiratory inorganics), ozone layer depletion, aquatic and terrestrial ecosystem impacts (ecotoxicity, acidification, nitrification/ eutrophication), global warming, non-renewable energy consumption, and mineral extraction. On a life-cycle basis, it cannot be concluded that a single energy option outperforms the others with regards to all the impact categories. However, it was concluded that utilizing the renewable energy options instead of the natural gas option for the base-load district heat generation reduces not only global warming and resource depletion impacts, but also carcinogenic, respiratory organics, aquatic ecotoxicity, acidification, and nitrification impacts. Wood pellets' life-cycle respiratory inorganics effect measured in terms of  $\text{kg}_{\text{eq}} \text{PM}_{2.5}$  is higher by one order of magnitude than the heat pump options and 14% higher than the natural gas option. The majority of the respiratory inorganics impacts from the wood pellet option are due to particulate emissions from the facility operation. Terrestrial impacts, which are the measure of soil toxicity and acidification impacts are higher for the wood pellet option than those of the natural gas and heat pump options. Terrestrial impacts associated with wood pellet utilization are due to soil contamination with heavy metals trace elements entrained in the bottom ash. Ozone layer depletion and mineral extraction impacts associated with the heat pump options are higher than those of wood pellets and natural gas options. Among the renewable options, it was concluded that the effect of sewage and geothermal heat pump options that operate based on low carbon electricity on global warming is less than that of the wood pellet option.

This thesis accepts the hypothesis in that:

1. Particulate emission levels from wood pellet combustion is below the regulatory limits in Vancouver, BC when a electrostatic precipitator flue gas cleaning system is used,
2. The cost of heat generation from the wood pellet option is comparable to that of the natural gas option and well below that of the heat pump options,
3. Based on the upstream environmental impacts of the energy options, a single energy option that outperforms others when considering all the impact categories at the same

time cannot be identified. However, it was shown that the impact of upstream production and transportation activities for the wood pellet option does not offset the global warming mitigation advantage of this option. The greenhouse gas equivalent upstream emission of the wood pellets option is in the same order of magnitude as the renewable heat pump options, and remarkably lower (less than 200 kg<sub>eq</sub> of the GHG emissions per MWh of produced district heat) than that of the natural gas option.

## **7.2.Strengths and limitations of the research**

The unique feature of the present study is that it includes an in-depth investigation of the impact of multi criteria on the performance of the wood pellet energy option as the primary energy source alternative for district heating. Other studies in the field, however, only focus on the evaluation of one decision making criterion and neglect or briefly address other important issues present in evaluation of such energy carriers.

The majority of the multi criteria decision analysis studies have focused at a high planning level such as the regional or national level, while less research is available on local energy systems with multiple energy carriers (Loken, 2007). In this regard, the multi criteria assessment (Chapter 3) of this research is among the few studies that focus on assessment of multiple energy carriers for a local energy system. Unlike the multi attribute theory methods such as SAW and AHP, the outranking methodology (PROMETHEE II) used for ranking the energy alternatives in Chapter 3 does not allow for compensation among criteria. This aspect is the advantage of the PROMETHEE method for comparison of fossil and renewable energy options where environmental and social criteria are emphasized.

Estimation of particulate emissions from wood burning boiler systems currently relies to a great extent on emission factors provided in the EPA AP-42 standard. However, EPA emission factors are the average of particulate emissions from various fuel types and combustion systems. There is very limited information regarding wood fuel quality, combustion technology and condition variations, which can dramatically affect particulate emission levels from such systems. In Chapter 4 the formation of particulate emissions is systematically explained and direct measurements from operating district

heating systems which utilize various types of wood fuels are provided. Such information can help identify the emission levels for such specific use as district heating systems. The life-cycle study of this research (Chapter 6) is the first study of its kind in Canada that evaluates the life cycle environmental impacts of energy source options for a district heating system.

The foremost assumption in acceptance of the hypothesis is that the issues raised by various stakeholder groups in the studied case are the major barriers to the selection of wood pellets as an energy option in district heating application. In other words, it is assumed that the considered case study is representative of the decision making process for selection of district heating energy sources in Vancouver. The acceptance of the thesis hypothesis may not be valid upon introduction of new criteria, new regulations or new technologies. The results of the life-cycle assessment are treated as informative values in evaluation of the hypothesis. In other words, it is assumed that the performance of energy alternatives with regard to various impact categories would not act as a screening criterion resulting in rejection of an alternative. The energy alternatives considered for the base-load system are assumed to be mutually exclusive. One of the criticisms of the multi criteria decision making methods is that ranking of alternatives, and in especial cases the best ranked alternative, may change when a new decision making criterion or a new non-optimal alternative is introduced to the model (Zanakis, 1998). Therefore, the conclusions derived from a multi criteria decision making analysis of Chapter 3 rely on the assumption that the major decision making criteria and energy alternatives are recognized in the study. The ranking of alternatives in this study may change if decision making parameters of the multi criteria model including criteria and alternatives set, criteria weight or alternatives/ criteria matrix change. The decision making results presented in Chapter 3 are based on the weights given to each attribute

The techno-economic study of the considered district heating system in Chapter 4 only included the components that would be different when utilizing various alternative energy sources. District heating network development, distribution water pumps, exchange systems, and revenues from district heating system operation were not included in the techno-economic model. Therefore the results of this study do not represent the

total costs and revenues from the district heating system, but rather indicate the incremental differences in the cost of various energy sources. Since the purpose of this study has been the comparison of various energy carriers for district heating application, this assumption does not affect the comparison results.

In the interpretation of the life-cycle assessment results in Chapter 6, the differences in time span and impact point in the creation of local and regional impacts should be recognized. For instance, impact categories such as human health related carcinogens and respiratory effects are mostly local impacts which should be investigated based on the level and risk of human exposure over a specific time period. However, the results of the LCIA are aggregative of upstream activities which combine various spatial and time frames over various stages of acquisition, production, and consumption. The severity of impacts on the local or regional environment is very much dependent on the exposure risk, duration, and emission levels, which are not reflected in the LCIA methodology. Therefore, for example, the high carcinogen effects of the natural gas option or respiratory inorganics of the wood pellets option in the life cycle analysis should not be used as a firm comparative scale, especially since these results do not suggest whether the impact levels created at the local level is higher than the known harmful or regulatory limits. Such results are better considered along with the upstream activity contributor chart. In this way it is possible to identify the upstream contributors and redirect study efforts to the specific process and location.

### **7.3.Future research directions**

The utilization of wood pellets as the fuel source in district heating systems in the Vancouver area was the focus of this research. In general, this fuel source has not been used to its capacity for energy production purposes in other regions of the province either. Study of barriers and issues for selection of this energy source option for district heating, as well as energy production in the province will increase the knowledge of the issues on the domestic market side.

The focus of this study was on heat only generation systems. Combined Heat and Power (CHP) systems have received increasing interest especially for district energy

generation purposes. Novel biomass-based CHP systems have been developed in recent years that are able to utilize biomass at higher overall efficiency compared to electricity or heat only generation systems. The study of such CHP systems for district energy (heat and electricity) generation is of interest for the near future.

Consideration of other natural uncontaminated woody biomass sources such as sawdust, shavings, and wood chips has been beyond the scope of this research. As the results of the particulate emission study in Chapter 4 show, it is expected that combustion of such materials, if pre-dried, produces controllable particle emission levels within the regulatory limits of Vancouver. Techno-economic and life-cycle assessment of utilization of such materials can be further studied and compared to those of wood pellets.

The results of the techno-economic study (Chapter 5) show that the operating costs of the peaking system accounts for more than 37% of the cost of produced heat in all options. This is due to high energy prices for natural gas used for peaking/backup systems. The district heating industry in BC relies a great deal on natural gas for peaking/backup systems because of the number of technical advantages of natural gas systems. These advantages include: advanced combustion technology, flexibility with regards to turn-down ratio, energy security due to well developed fuel transmission networks, and low initial investment. The economic and technical feasibility of utilizing renewable energy sources such as wood biomass for peaking/backup in district heating systems may be further studied to consider the requirements of the peaking/backup systems.

Review of literature on particulate emission levels from various biomass combustion technologies reveals that studies on direct measurement of particulate emissions from utilization of various forms of wood fuels in suspension burner and gasification technologies are not available. More research effort is required to quantify emissions from these technology options that have recently got more attention in district heating applications. Such information could help in building public confidence in the utilization of wood biomass using these technologies.

The results of the life-cycle assessment section of this thesis (Chapter 6) can be used to identify the main inventory contributors of certain environmental impacts, then design and perform research studies to mitigate such impacts. For example, mitigation of natural gas extraction effects on the regional ecosystem through alternative processes could be studied further, or for the wood pellet option, further studies could be carried out to investigate how the life-cycle impacts of airborne emissions during manufacturing wood pellets can be reduced. Also it has been concluded that heavy metals entrainment in the bottom ash of wood pellet combustion is a major contributor to the terrestrial impacts of this option. Ash management scenarios and practices to reduce or eliminate the possible terrestrial impacts of heavy metals release to the soil should be further studied.

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# Appendix- City of Vancouver's memorandum regarding the energy source for the Southeast False Creek district heating centre

## LATE DISTRIBUTION FOR COUNCIL - APRIL 17, 2007 CITY OF VANCOUVER



ADMINISTRATIVE REPORT

# A15

Report Date: April 13, 2007  
Author: R. Birch  
Phone No.: 604.873.7280  
RTS No.: 06698  
VanRIMS No.: 11-2000-14  
Meeting Date: April 13, 2007

TO: Vancouver City Council  
FROM: General Manager of Engineering Services  
SUBJECT: Neighbourhood Energy Utility Heat Source Technology

### RECOMMENDATION

THAT Council receive this report for INFORMATION

### GENERAL MANAGER'S COMMENTS

The General Manager of Engineering Services submits this report for INFORMATION.

### COUNCIL POLICY

On March 2, 2006, Council approved in principle the creation of the Neighbourhood Energy Utility and authorized preliminary design work for a sewer heat recovery plant and further investigation of biomass as an alternative heat source for Phase 1 or later phases.

On December 14, 2006, Council received a report entitled "Neighbourhood Energy Utility - Evaluation of Heat Source Options". This report outlined the relative merits of Sewer Heat and Biomass Energy as heat sources for Phase 1 of the Southeast False Creek Neighbourhood Energy Utility. The report identified biomass as the preferred option, based mainly on the superior greenhouse gas (GHG) emission performance and relatively low technical risk of this option. Council authorized the Neighbourhood Energy Utility Steering Team to submit an air quality permit application in support of biomass energy for Phase 1 of the Southeast False Creek project. Further, Council authorized the Steering Team to review the results of the public consultation process after 30 days in relation to the impact on project schedule and either:

- i) continue with the permit application process and development of biomass heat, OR
- ii) cancel the permit application and proceed with design activities for the use of sewer heat

#### PURPOSE

The purpose of this report is to advise Council that, based on the schedule delays associated in obtaining a biomass air quality permit and on recent progress resolving the technical viability of sewer heat recovery, the NEU Steering Team has selected the second option noted above for Phase 1 of the SEFC NEU. Consequently, staff will be notifying the GVRD that the permit application for a biomass heat source in Phase 1 will be withdrawn.

#### BACKGROUND

The December, 2006 Report to Council noted that a biomass heat source facility would be subject to GVRD air quality regulations and would require the issuance of an emissions permit. The permit review process includes a public consultation component, and the length of time necessary to process the permit application can vary significantly based upon the feedback received during public consultation.

Due to the need to meet the development schedule of buildings in South East False Creek, and uncertainties related to the length of time required for GVRD approval, the report proposed that an assessment would be made after the first 30 days of the public process. The NEU Steering Team was given authority by Council to either cancel the permit application and proceed with design activities for the use of sewer heat or continue pursuance of an air quality permit for biomass, dependent upon the outcome of this assessment.

A biomass air quality permit application was filed with the GVRD in February, 2007. Public consultations began on March 1. Direct notification was provided to the surrounding community and various Southeast False Creek stakeholder groups, and advertisements were placed in local newspapers. Open houses were held on March 13 and March 15, and three additional information sessions were held between March 22 and March 27 with stakeholder groups.

An assessment of the feedback received and its implications on project schedule has now been performed, in accordance with Council's instructions.

In the past three months, further work has been done by the City's consultants to investigate technical challenges related to the viability of sewer heat recovery. This work has determined that solutions can be found to key issues, and the technical risk associated with a sewer heat recovery system has been reduced significantly. These issues included:

- Concerns about sewer flow limitations, which can be solved by using the Nelson Force Main Sewer as a source of "top up" supply
- Concerns about the ability of the heat pump to operate in low heat demand conditions, which can be addressed by adding a small condensing natural gas boiler to the design

- Concerns about the potential for delays arising from the need for certification of specialized equipment originating in Europe, which can be mitigated by early ordering of the necessary equipment.

## DISCUSSION

### 1. Assessment of Public Process

The public process to date with various stakeholders (including individual residents, resident associations, Southeast False Creek Developers, various non-governmental organizations and others) has identified a number of concerns related to biomass:

- perception that wood combustion generates harmful emissions
- perception that truck delivery of wood pellet fuel would have undesirable impacts
- concern that environmental impacts have not been adequately assessed.

Other concerns related to questions that staff were unable to answer at this stage in the project's design and implementation. Specific concerns were:

- concern about appearance of the energy centre/stack
- lack of detailed design information for the proposed equipment
- concern about lack of certainty of source and quality of fuel supply.

Staff believe that all of the above perceptions and concerns could, with sufficient time and further work, be addressed and resolved to the satisfaction of most stakeholders. However it is staff's judgement that there is insufficient time available in this project schedule to carry out the necessary public process in support of an air quality permit application for Phase 1 of the Southeast False Creek Neighbourhood Energy Project. Delays of between 2 and 6 months, or longer are anticipated. These delays are not manageable within the project schedule.

### 2. NEU Steering Team Decision

With this information about the schedule implications of biomass, and taking into consideration the progress made to mitigate technical risk associated with sewer heat recovery, the NEU Steering Team has decided to continue with energy centre design activities using sewer heat recovery as the base heat source. Consequently, staff will be notifying the GVRD that the City's application for an air quality permit for the Phase 1 heat source will be withdrawn.

### 3. Future Potential for Biomass

This technology choice will generate very significant GHG reductions, though less than would have been achieved with biomass.

It is important to note that a decision to proceed with sewer heat as the primary heat source for Phase 1 is no reflection of the viability of biomass energy as a sustainable heat source option for other potential district heating or building development projects. Biomass has the advantage of being able to generate heat using any one of a number of waste products. As

well, it continues to be recognized widely as a reliable heat source with superior GHG emission performance.

#### FINANCIAL IMPLICATIONS

As reported in the December 12, 2006 Council report, the projected long term costs associated with sewer heat recovery is approximately equivalent to the wood pellet biomass option. Further work will be done during the upcoming design process to update cost information and Council will be advised as to any issues which may arise as a result.

#### CONCLUSION

The Neighbourhood Energy Utility seeks to achieve Council policy objectives by achieving greenhouse gas emission reductions, consistent with the directions established in the Community Climate Change Action Plan. Adoption of sewer heat recovery for Phase 1 of the Neighbourhood Energy Utility demonstrates the City's continuing leadership in applying innovative concepts and technologies to achieve these objectives.

\* \* \* \* \*