FOREST RESIDUES TO ENERGY:

LOCAL AIR QUALITY, HEALTH RISKS AND GREENHOUSE GAS EMISSIONS

by

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Abstract

Local impact assessment of biomass-based district energy systems (DES) is still in its infancy. There has been a lack of appropriate assessment methods for parameters with broad variability on local scale, and lack of DES impact assessments. This study investigates how would: 1) the inclusion of site-specific terrain, land use and microclimatic characteristics, variable population density and breathing rates affect accuracy of assessments on local air quality and health; 2) an incremental increase of $PM_{2.5}$, NO_x and CO concentrations from DES contribute to ambient air quality and population exposure, 3) life-cycle GHG emissions from DES contribute to global warming, and 4) the introduction of biomass affect economics of DES compared to the fossil fuel-based DES.

Utilizing dispersion modeling the study established an assessment approach which confirmed the need for inclusion of population dynamics, site-specific microclimatic characteristics, and diurnal circulation patterns. Otherwise, health risks could potentially be underestimated by more than 20%. Applying this approach on a small-scale biomass gasification plant (BRDF), the study concluded that the health impact was the highest for NO_2 (677 DALY) when all energy was produced by biomass, and for $PM_{2.5}$ (64 DALY) if all energy was produced by natural gas. Complete replacement of Power House (PH) by one biomass plant can result in almost 28% higher impact compared to 513 DALY when both BRDF and PH are operational. NO_2 emissions from the BRDF exceeded the air quality objectives (BCAQO) in all seasons except during summer. Although overall incremental contribution of $PM_{2.5}$ is at least one order of magnitude lower than BCAQO, the maximum $PM_{2.5}$ emissions from the PH could adversely add to the already high background concentrations.

Meeting energy demand solely by an expanded full-scale BRDF from locally supplied biomass reduces GHG annually to 3.81E+06 kg CO_{2eq} from 7.08E+07 kg CO_{2eq} when energy was produced solely by the current PH. An introduction of biomass increased total costs by $19 M compared to existing PH, but saved $8.4 M in carbon tax over plants' lifetime. $3.3 M of societal damages could be avoided over plants' lifetime in case of combined use of natural gas and biomass.

Lay Summary

This research improves current methods for assessing impacts of biomass-based district heating systems. It is confirmed that introducing site specific characteristics such as population dynamics, local meteorological conditions along with outdoor pollutant concentrations could more accurately evaluate local air quality and population health risks. The study further evaluates impacts of a biomass plant located at the University of British Columbia, Vancouver campus which is operational since 2012 and supplies heat to almost 20% of campus heat demand. The study found that the choice of fuel (wood versus natural gas) will have impacts on a global scale in terms of reduced impacts on global warming, whereas the choice of plant location balanced with techno-economic benefits should be a primary consideration for minimizing local impacts (population exposure and local air quality) regardless the fuel type. The development of biomass plants could be costly but savings exist in carbon taxes and societal damages.

Preface

The topic of this doctoral dissertation was deliberated during the discussion with my academic adviser Dr. Xiaotao Bi and The Bridge Program Director Dr. Michael Brauer. The entire research reported here was conducted by the author, Olga Petrov and included: developing thesis objectives and research questions, conducting systematic literature review, designing the research program, gathering and evaluating data, developing and applying a novel impact assessment methodology for community-based district energy systems in consort with developing and running airborne pollutant dispersion, population exposure and life cycle modeling scenarios, and analyzing and interpreting the results. The following parties were regularly consulted: UBC's Engineers at the Bioenergy Research and Demonstration Facility (BRDF), Power House (PH) and Campus + Community Planning; Nexterra Energy Corp. and Cloverdale Fuel Ltd.

Parts of this research were published:

- A version of chapters 1 and 2 have been published. **Petrov, O.** (**2012**). Forest Residues to Energy: Is this a pathway towards healthier communities? National Collaborating Centre for Environmental Health. Evidence Review. Available from: http://www.ncceh.ca/sites/default/files/Forest_%20Residues_to_Energy_Mar_2012.pdf. I conducted systematic literature review and wrote the whole manuscript. Dr. Bi and Dr. Brauer provided invaluable comments and edits.
- A version of chapters 2 and 3 has been published. **Petrov, O**., Bi, X., & Lau, A. (**2015**). Impact assessment of biomass-based district heating systems in densely populated communities. Part I: Dynamic intake fraction methodology. *Atmospheric Environment*, *115*, 70–78. https://doi.org/10.1016/j.atmosenv.2015.05.036 . I conducted all data

collection, modeling and wrote the manuscript. Dr. Bi and Dr. Lau provided invaluable comments and edits.

- A version of chapter 4 has been published. **Petrov, O**., Bi, X., & Lau, A. (**2017**). Impact assessment of biomass-based district heating systems in densely populated communities. Part II: Would the replacement of fossil fuels improve ambient air quality and human health? *Atmospheric Environment*, *161*, 191–199. https://doi.org/10.1016/j.atmosenv.2017.05.001. I conducted all data collection, modeling and wrote the whole manuscript. Dr. Bi and Dr. Lau provided invaluable comments and edits.
- A version of chapters 5 and 6 is under preparation for publishing: **Petrov, O**.; Xiaotao Bi, Anthony Lau. **(2017).** Global impacts assessment and economic analysis of woody biomass as an alternative to fossil fuels in district heating applications. I wrote the whole manuscript; conducted literature search on carbon neutrality; collected and processed consumption data for natural gas, fuel oil and biomass used in the UBC Power House (PH) and Bioenergy Research and Demonstration Facility (BRDF); estimated emissions; performed LCA modeling, and economic analysis. Data on biomass supply are based on the work prepared for the UBC SEEDS project, published at: https://sustain.ubc.ca/courses-teaching/seeds-program/seeds-sustainability-library. Dr. Bi and Dr. Lau provided invaluable comments and edits.

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List of Acronyms

ADES	Academic DES
AQO	Air Quality Objectives (provincial – BC)
BC MoE	British Columbia Ministry of Environment
BRDF	Bioenergy Research and Demonstration Facility at UBC campus
CAAQS	Canadian Ambient Air Quality Standard
CALPUFF	CALifornia PUFF Model
CEC	Campus Energy Centre
CHP	Combined heat and power
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DES	District energy system
DH	District heating
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
ESP	Electrostatic precipitator
FU	Functional unit (LCA)
GIS	Geographic Information System
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFV	Lower Fraser Valley
MM5	Mesoscale Meteorological Model, Version 5
MV	Metro Vancouver
NG	Natural gas
NMVOC	Non-methane volatile organic compounds
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
PH	Power House (at UBC)
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter less than 2.5µm
PM_{10}	Particulate matter with a diameter less than 10µm
PV	Present Value (used for economic assessment)
RF	Radiative Forcing
SO_x	Sulphur oxides
UBC	University of British Columbia
VOC	Volatile organic compounds

List of Symbols and Selected Units

Symbol	Unit	Definition
BR	m^3/person/day	Breathing rate
C	$\mu g/m^3$	Pollutant ambient concentration at a receptor
CO_{2eq}	kg	Unit for GHG, calculated by multiplying emissions by GWP
EF_{Heatlh}	DALY/kg	Human health toxicological effect factor
EF_{NG}	g/GJ	Emission factor for natural gas combustion (converted from kg/mmBtu)
EF_{OIL}	g/GJ	Emission factor for oil #2 combustion
EF_{WG}	g/GJ	Emission factor for wood gasification
H_{EF}	m	Effective stack height
HHV	MJ/kg	Higher Heating Value
iF	ppm	Impact fraction
IS	DALY	Health-related Impact Score
m	g	Mass of a pollutant emitted from a source
MC_W	%	Moisture content of wood, wet basis
MC_D	%	Moisture content of wood, dry basis
Ϭx	m	Standard deviation of Gaussian distribution in the downwind direction
Ϭy	m	Standard deviation of Gaussian distribution in the cross-wind direction
Ϭz	m	Standard deviation of Gaussian distribution in the vertical direction
Q	g/sec	Pollutant emission rate

Unit	Definition
Btu	The British thermal unit equal to 1,055 joules
DALY	Disability-adjusted life years
EJ	Exajoule, equal to 10^{18} joules
GJ	Gigajoule, equal to 10^9 joules or 10^3 MJ
KLBS	Kilopounds
KSCF	Kilo Standard Cubic Feet (at 21ºC and 101.325 kPa)
kWh	Kilowatt hour
lb	Pound
MMBtu	10^6 Btu , also known as mmBtu
MW_h	Megawatt hour
µg	Microgram, equal to 10^{-6} g
ODMT	Oven dry or Bone dry (BD) metric tonne – mass of wood after all moisture has been evaporated
ppm	Parts per million (v/v), equal to 10^{-6}
t	Tonne, metric, equal to 1,000 kg
TJ	Terajoule, equal to 10^{12} joules

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Doctoral studies at UBC were my much wanted and much appreciated journey of personal and professional growth. For this achievement I offer my enduring gratitude and admiration to my supervisor Dr. Xiaotao Bi, for sharing his expertise, his guidance, patience and trust over the years. I sincerely thank Dr. Anthony Lau and Dr. Taraneh Sowlati for constructive comments, suggestions and encouragement throughout my studies and research. I appreciate the time and insightful questions and comments from my examining committee: Dr. Zhongchao Tan, Dr. Madjid Mohseni, Dr. Kasun Hewage and Dr. James Brander.

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Data and consultation provided by Jeff Giffin, Joshua Wauthy and UBC Campus + Community Planning, Nexterra Systems Corp., Cloverdale Fuels Inc., Metro Vancouver and Lakes Environmental were crucial for my research and were much appreciated. A special thank you I owe to Bridge fellows: Siduo Zhang, Alicia LaValle, Ther Aung, and Jackie Yip, and BBRG (Biomass and Bioenergy Research Group) members for cooperation but above all for their friendship, laughs and perseverance which kept me strong during the most difficult and challenging periods of my life.

To my family and friends whose love and support inspired me to advance, I promise undivided attention in years to come.

Dedication

Dedicated with love and pride to my husband Aleksandar Petrov, PhD (Mech. Eng.), whose achievements and passion for biomass research were interrupted too soon by illness.

Chapter 1: Introduction

1.1 Background

1.1.1. Global drivers and perspectives on energy production and utilization

Climate change has been a focus of environmental research for decades now. Independent analyses conducted by thousands of scientists across the world undoubtedly confirmed the exceptional changes of the Earth's climate system since 1950s observed as warming of the atmosphere, sea level rise and diminished amounts of snow and ice (IPCC, 2015).
Concentrations of greenhouse gases (GHG), especially those of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) mainly generated by human activities, are rapidly increasing in the atmosphere. Between 2000 and 2010 these emissions were estimated to be higher than ever and, along with other anthropogenic factors, are claimed to be *extremely likely* the dominant cause of atmospheric warming since the second half of the 20th century (IPCC, 2015).
There is evidence that anthropogenic (human made) pollutants contribute more to overall atmospheric content of gases and particles than it would exist or change at a certain rate naturally. As presented in Figure 1.1 from the latest IPCC report (AR5), anthropogenic emissions of greenhouse gases (GHG), especially those of carbon dioxide (CO_2) from industrial practices and burning fossil fuels, continue to increase, reaching 49 ± 4.5 $GtCO_{2eq}$[1] in 2010. It is estimated that 47% of increased GHG emissions between 2000 and 2010 originates from the energy sector while industry and transportation sectors contributed with 30% and 11% respectively. In addition to recognizing CO_2 as a major contributor (76% of total GHG in 2010), CH_4 contributed 16%,

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[1] CO_{2eq} – Carbon dioxide equivalent emissions of CO_2, CH_4, N_2O and fluorinated gases based the 100-year Global Warming Potentials (GWP), using IPCC Second Assessment Report (SAR).

N_2O contributed around 6.0%, and 2.0% came from fluorinated gases (IPCC, 2015). It is determined that steady population growth and steep economic growth based intensively on coal combustion present the major cause of CO_2 emissions. Therefore, reducing carbon intensity of the world's energy supply presents challenges for years to come.

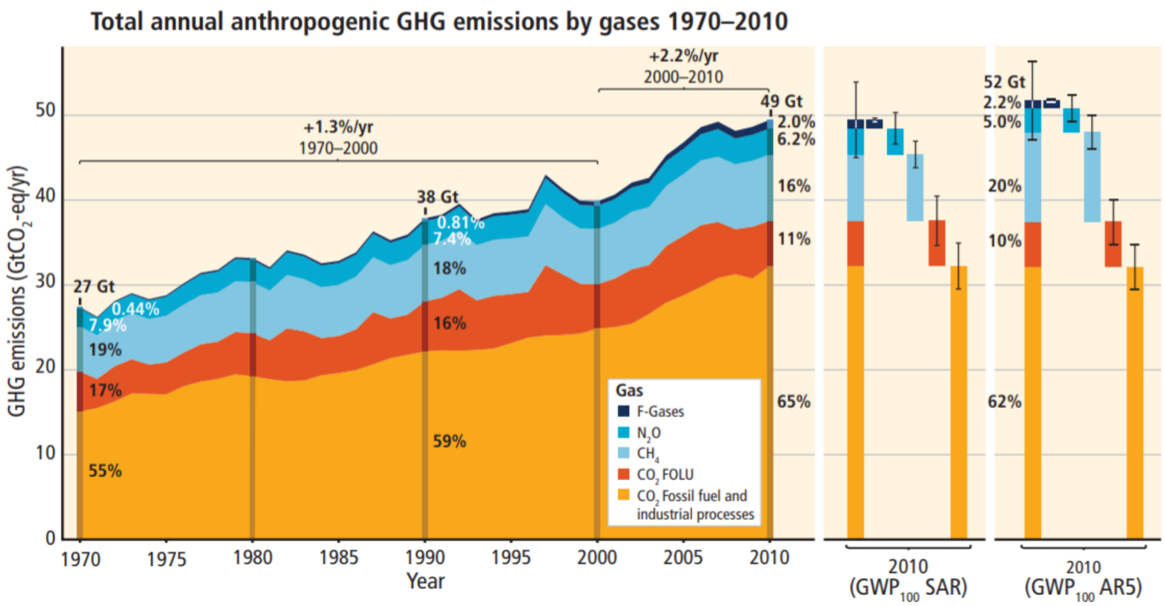

Figure 1.1 Total annual anthropogenic GHG emissions by gases [$GtCO_{2\text{-eq}}$/yr] for the period 1970 to 2010.
Adopted from: (IPCC, 2015), Figure 1.6, pg. 46).[2]

The U.S. Energy Information Administration (EIA) projected increase of energy use by 48% from 2012 to 2040 (Figure 1.2) by using known demographic trends and policies which were in place at the time of their analysis (EIA, 2016). Global energy consumption is projected to be especially pronounced for non-OECD[3] countries such as China and India where rapid economic growth requires extensive energy use. Such countries are projected to increase energy demand by

[2] FOLU - Forestry and Other Land Use; F-gases - fluorinated gases covered under the Kyoto Protocol; CH_4 - methane; N_2O - nitrous oxide.
[3] OECD - Organization for Economic Cooperation and Development.

71% by 2040 from 2012 levels, whereas more mature and stable OECD economies are projected to have 18% of increase in energy demand for the same time frame.

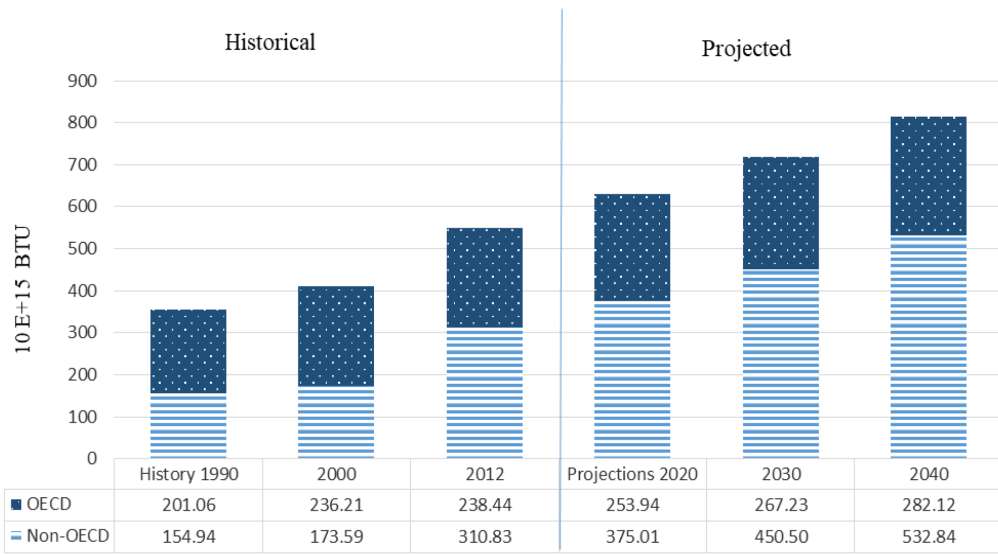

Figure 1.2 World energy consumption from 1990 to 2040 projections in quadrillion Btu.[4]
Source: Based on EIA (2016).

Some of the parameters that will influence the type of energy sources used include energy security and energy prices, as well as impacts on the environment. Since fossil fuels used for energy production are considered as the main source of GHG emissions, their replacement with cleaner and renewable energy sources are a world-wide policy approach. Based on the EIA report (EIA, 2016), renewable energies lead the global energy demand with an annual average growth rate of 2.6%, followed by an increase of 2.3% in nuclear energy use and 1.9% increase in natural gas, a least carbon intensive fossil fuel (EIA, 2016).

Canada with its vast non-renewable and renewable resources has a challenge but also the

[4] Quadrillion British thermal units (Btu) = 10E+15 BTU which is equal to 1.05587E+19 J.

opportunity of selecting cost effective and environment-friendly energy options. Natural gas is a fossil fuel convenient for many energy applications such as process heating and steam generation in industry, water and space heating in buildings and cooking in residential units. Natural gas accounted for 33% of total primary energy production in 2013, 34.1% in 2014 and reached marketable production of 14.2 Bcf/d [5] in 2014 (Natural Resources Canada (NRC), 2015). Supply of natural gas greatly exceeds domestic demand but Canadian exports are directed to only one market, the United States, which poses challenges due to lack of diversity in markets (Canada's Natural Gas, 2017). Primary domestic users are industrial and commercial sectors. While industrial consumption depends on economic conditions, natural gas demand and consumption for heating will also depend on weather condition and population growth. Between 1990 and 2008, population grew about 20% as did the number of households and living space, leading to 14% increase in residential energy use but only 8% increase in greenhouse gases (GHG) emissions due to the use of cleaner energy sources and increased energy efficiency (Government of Canada, 2011). According to Fallahi et.al. (2016), Canada still belongs to countries with steady rather than explosive pattern of energy consumption.

1.1.2. Environmental concerns and alternatives to fossil fuels for energy production

Although natural gas, which is widely used for heating and electricity production in British Columbia (BC) and Canada, is a relatively clean-burning fossil fuel, it still contributes to greenhouse gases (GHG) emission. Ecosystem deterioration ranging from local- to global-scale due to the extensive use of fossil fuels has been well documented over the past few decades. In

[5] Bcf/d = Billion cubic feet per day = 28316846.592 m^3/d = approximately equal to one trillion BTUs.

recognizing these issues, the province of British Columbia sets a suite of policy actions proposing, amongst others, the use of BC's plentiful biomass resources for energy generation. One of the most comprehensive strategy is the 2007 BC Bioenergy Plan which outlines a clean energy vision for the Province, followed by the BC Bioenergy Strategy in 2008 (BC Ministry of Energy, Mines and Petroleum Resources, 2008). In addition to a well-known BC's low carbon electricity generation profile which largely relies on hydropower generation, the mentioned documents further elaborate on the energy-related goals with one of which referring to utilization of biomass through the bioenergy sector development, generation of energy from pine beetle infected wood, development of the BC biomass inventory and investments in bioenergy research and development (BC Ministry of Energy, Mines and Petroleum Resources, 2008). The main goals of BC energy plans and strategies in diversifying energy resources and increasing energy security is to focus on clean energy in order to minimize impacts on climate and the environment, and protect human health.

Biomass refers to all the living matter available in different forms such as: vegetation, agricultural waste, and residues from forests and industrial operations, animal manure, all of which could be used as energy sources (Searcy and Flynn, 2010). Forest residues refer to a non-merchantable woody biomass, such as tree species and residues from logging practices, including roadside and in-forest wood. In addition, forest residues from industrial operations, such as mill wood waste (sawdust, shavings, bark), are commonly considered as woody biomass - convenient for use as a fuel or energy source. Biomass applications either through district heating or through decentralized heating options with wood pellets are seen as a good solution for Canadian remote communities in terms of reduction of GHG and heating costs, and increase of energy independence (Stephen et al., 2016). Uncertainty in forest bioenergy supply chains exists partly due to economic fluctuations, which also affects other energy industries, yet additional complexities exist (Shabani and Sowlati, 2016).

1.1.3. Availability of biomass resources and district energy systems in British Columbia

British Columbia has abundant forest resources which could be used for energy in many ways**.** More than 400 million hectares of Canada's land (44%) are forests; most under provincial jurisdiction. The largest user of biomass (mostly forest residues) for energy is the Canadian forest products industry which generates almost 60% of its energy from this renewable source (Bradley, 2006). An Inventory of the Bioenergy Potential of British Columbia (Ralevic and Layzell, 2006) identified forest residues from industrial operations, such as mill wood waste (sawdust, shavings, bark), and forest residues from logging practices, as significant woody biomass resources in British Columbia. The same industrial sector, especially pulp and paper industry, utilizes such residues to generate energy (heat and electricity) for its processes. Other studies evaluated pine beetle damaged wood as an additional forest residues-type of feedstock for energy (Mahmoudi et al., 2009) for the next 15years (Schwab et al., 2009; Envirochem Services Inc., 2008), and considered its impacts on the forest sector and province's economy. All of these resources, if used for energy, have potential to provide many benefits to the province: minimizing wood-waste which would otherwise be either burnt (increasing air pollution) or sent to landfills (increasing GHG emissions, carbon footprint[6]); development of new biomass-based technologies, and creation of jobs.

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[6] Carbon footprint – is defined in many ways but in essence accounts for total amounts of CO_2 and other GHG emitted over the full life cycle of a process or product. It is expressed as grams of CO_2 equivalent per kilowatt hour of energy generation (g CO_{2eq} /kWh) (POST, 2006).

Woody biomass could be thermaly converted to energy in many ways. The most traditional applications include domestic applications in fireplaces and stoves and large scale applications in advanced energy-efficient wood combustion (AWC) systems with air pollution controls in place for heating and electricity generation. These systems are widely used in Europe and became attractive in North America in applications such as district energy systems. More efficient boilers will result in lower emissions than traditional wood combustion system, however, emissions may not be as low as for oil or natural gas boilers so engineered pollution controls are likely to be needed (Chandrasekaran et al., 2011).

Major biomass energy technologies include: a) *Direct combustion* of pellets, briquettes, or wood chips with heat or steam as the major product which can be further directed to turbines to produce electricity; b) *Pyrolysis*, a high-temperature, anoxic[7] thermo-chemical process in the absence of oxygen to produce bio-oil, biochar and combustible gases which can be further used for heat and power generation, and c) *Gasification*, another high-temperature thermochemical process which converts biomass under lean oxygen conditions into synthetic gas which can be further used for heat and power, and chemical production (Rubio-Maya et al., 2011).

District energy systems (DES) have potential to provide effective energy solutions. Configured as centralized production of steam or hot water for heating and in some cases electricity for local community (neighborhood), DES are characterized by lower infrastructure costs, lower overall

[7] Anoxic – the absence of oxygen.

emissions and reduced cost compared to conventional distributed heating systems mainly based on natural gas. These systems can use a variety of conventional and renewable sources.

Analysis of Swedish energy policy in terms of its effects on district heating (DH) economic performance and climate change mitigation (Gustavsson et al., 2007) demonstrated that the most cost-effective policy option is the investment in biomass-based combined heat and power (CHP) systems in the case of applicable taxes and policies such as Tradable Green Certificate (TGC). In the case when national taxes and policies are excluded, natural gas fired DH becomes a superior investment (Difs et al., 2010). About 80% or 4 million residents in Sweden are connected to district heating systems (Swedish District Heating Association, 2014). More than 400 district heating companies supply 98 % of the district heating or some 1.6 million households in Denmark (Danish District Heating Association, 2014).

Biomass-based DES (Fiorese et al., 2014), configured as combined heat and power (CHP) or heat only production systems (DH), are rapidly growing in Canada. There were merely 3 such projects in 2009 but it increased to more than 100 projects in the last few years (CIEEDAC, 2015; Bradley, 2012) with a total heating capacity of 121 MW_{th} or 3.4% share of Canadian district energy heating capacity from all energy sources (CIEEDAC, 2015). Utilization of bioenergy could be beneficial to Canada's and BC's economy, providing improvements in energy efficiency and reduction in greenhouse gas (GHG) emissions. British Columbia also has a number of DES projects which have either already commenced or under development with special emphases to renewable energy resources (Province of BC, 2012). Table 1.1 outlines some of the biomass energy projects in the province.

Table 1.1 Examples of biomass DES projects in British Columbia.

Project	Location	Capacity	Benefits
Dockside Green (Dockside Green Energy, 2008))	Victoria	2 MWth	• Supplies hot water to the Dockside Green community, • Enables Zero Carbon footprint of the site.
Kruger Products (Canadian Biomass), 2009)	New Westminster	40,000 lbs/h of process steam	• Displace about 445,000 GJ of natural gas annually • Reduces GHG from the plant for 22,000 t per year
UBC Biomass Research and Demonstration Facility (BRDF) (UBC, 2015a)	UBC, Vancouver	6 MWth 2 MWel	• BRDF provides a quarter of campus heating needs, • Eliminates 14% of campus GHG emissions.
UniverCity Sustainable Energy Project (SFU, 2016)	SFU, Burnaby	10 MWth	• 2,400 t of GHG reduction (85% reduction from heating, 69% reduction from all sources), • Reduces the overall cost of energy to the customer.
Revelstoke Community Energy System (FVB Energy Inc., 2017)	Revelstoke	1.5 MWth	• Diverts 70,000 t of wood residue annually, from beehive burners and improves air quality, • Reduces GHG for 3,200 t annually, • Supplies heat for several buildings and steam for Downie's sawmill drying kilns.
Prince George District Heating (FVB Energy Inc., 2017)	UNBC, Prince George	7.5 MWth	• Reduces GHG for 1,900 t annually, • DES connection to the new Wood, Innovation and Design Centre (WIDC) • Provides heating for several downtown buildings and enables research at UNBC.

1.1.4. Public perception and acceptance of biomass systems

Since energy crisis in 1970s, those who were promoting political agenda and economic and environmental priorities influenced energy policies world-wide. While there have been extensive discussions on wood for energy with a focus mainly on resource availability and economic needs, public opinion has been rarely heard. As pointed out by Mittlefehldt (2016), conflicting narratives around competing energy alternatives materialized in the direction of creating ecological and public health risks associated with biomass-based energy systems. While supporters promoted biomass as a decentralized energy resource by nature, opponents feared that the development of biomass-based energy sources would create local centers of power, different from fossil fuel related political structures. Social constrains like using forested areas for recreation or cultural activities where harvesting is not allowed, or other land uses issues can reduce biomass mobilization (Kraxner et al., 2016). Thus, understanding and considering parameters of social acceptance of a novel technology by including citizen in the decision making process is crucial for the deployment of local district heating systems in communities (Zaunbrecher et al., 2016). Similar findings were presented by a German longitudinal study on public acceptance of decentralized power generation by biomass and relevant influencing factors (Kortsch et al., 2015). The study emphasized a multi-actor and multi-dimensional character of the acceptance process ranging from individual to regional perspectives and factors. While regional economic development and benefits could be readily accepted as positive factors, individual and local scale factors rather revolve around perceived negative impacts caused by increased noise due to truck traffic, smells etc. However, public involvement in the planning process and increased awareness and information diffusion certainly increase the level of acceptance of biomass projects on the local level. A Swedish study (Kautto and Peck, 2012) gave emphasis to stakeholder involvement and new biomass resource mobilization within regional planning while leaving biomass sources in general to national planning.

In general, it could be deduced that the critical factors for the diffusion of bioenergy for district heating are both economic and non-economic in nature (Toka et al., 2014; Wright et al., 2014; Aguilar et al., 2011), since main barriers range from economic, technological to cultural and psychological. While the main benefits could be seen in the reduction of CO_2 emissions, still the negative image of system's operation and not well understood impacts of airborne emissions may nurture resistance for their adoption. DES are of a much lower capacity (a few MW_{th}) with consequently lower emission rates from shorter stacks (< 20 m) than large power plants (> 100 MW_{th}) with tall stacks (> 200 m) (Zhou et al., 2003). This indicates the need of considering DES impacts on a much smaller spatial/temporal scale than a commonly practiced large and remote power plant in order to address the "Not-In-My-Backyard" health concerns. In addition, better connections between urban planning and energy policy development are necessary for the acceptance of DES (Gabillet, 2015). A successful process of transition to biomass DES in Sweden (Di Lucia and Ericsson, 2014) can serve as a good guidance for the process of adopting different renewable energy choices and biomass in particular.

The full impact assessment of DES, especially those using biomass, with respect to local air quality and community health has not yet been properly investigated and addressed. Very few studies started recognizing the importance of local and urban health impacts of near-by stationary sources. For example, Jonsson and Hillring (2006), pointed out that meteorological and topographical conditions need to be considered with small-scale DES due to near-source high pollutant concentrations. Another study (Curci et al., 2012) showed increased NO_2 emissions from a proposed biomass plant.

Systematic literature review (Chapter 2) revealed that previous studies relied on many assumptions and did not account for dynamic population changes and actual spatial and temporal variations of ambient air quality (Martenies et al., 2015), or relied on selected archetypal environments and emission sources (Humbert et al., 2011), which points to the lack of an appropriate impact assessment method for small-scale stationary sources.

The lack of knowledge about biomass-based DES impacts is reflected by many rejected biomass-based DES proposals by communities that are concerned about increased health impacts in recent years. One of the well-known projects was a proposed biomass DES for the Vancouver's Olympic Village which was abandoned in 2006. According to the "City of Vancouver's memorandum (Appendix A), regarding the energy source for the Southeast False Creek district heating centre" (Ghafghazi, 2011):

> *"The public process to date with various stakeholders (including individual residents, resident associations, Southeast False Creek Developer, 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 would have an undesirable impacts*
> - *Concern that environmental impacts have not been adequately assessed."*

Therefore, two major knowledge gaps with respect to biomass-based DES were identified:

- Knowledge gap 1: the lack of appropriate and accurate impact assessment methodology for parameters with extensive variability on local scale. Such variability may potentially influence the outcomes (impacts) which otherwise would not be noticed and considered;
- Knowledge gap 2: assessment of biomass-based DES impacts on local ambient air quality and human health which will be based on impact assessment methods with higher accuracy and inclusion of local, site-specific characteristics.

The University of British Columbia initiated the development of a small-scale biomass research and demonstration facility (BRDF) at the Point Grey campus in Vancouver to enable not only research and demonstration of biomass conversion technologies but also quantification and potential reduction of air emissions and a range of environmental impacts of biomass applications for community-based energy systems. This research work therefore presents timely and much needed study to contribute to our knowledge on potential impacts and sustainability characteristics of community-based biomass energy systems.

1.2 Thesis objectives and research questions

In order to address knowledge gaps and to address community and other stakeholders' concerns, this study sets the following primary objectives:

a) Improve current approach (methodology) for air quality and integrated health impact assessment of community-based biomass district heating systems; b) Investigate, by applying the proposed methodology to a case study, the impacts of signature pollutants such as airborne fine filterable particles ($PM_{2.5}$), oxides of nitrogen (NO_x), and carbon monoxide (CO) on ambient local air quality, population exposure potential expressed by inhalation intake fraction (iF) and health risks expressed by impact score (IS).

Additionally, this study also aims to:

c) Update an in-house Life Cycle Inventory database for British Columbia with the foreground fuel supply and conversion data for the UBC Bioenergy Research and Demonstration Facility (BRDF); d) Investigate global impacts of greenhouse gas (GHG) emissions over the entire life cycle in terms of environmental damages such as climate change and human health; e) evaluate sustainability of district heating options connecting their environmental, social and economic characteristics.

In doing so this study addresses the following research questions:

1. How would the inclusion of site-specific terrain, land use and microclimatic characteristics, variable population density and breathing rates improve accuracy of local air quality and population health impact assessment of community-based biomass energy systems?

2. How would an incremental increase of $PM_{2.5}$, NO_x and CO concentrations from investigated biomass DES contribute to local effects such as ambient air quality and population exposure?

3. How would life-cycle GHG emissions from the investigated biomass DES contribute to global warming?

4. Considering capital, operational and maintenance (O&M) costs and externalities, how would the introduction of biomass-based DES affect economics compared to fossil fuel-based DES?

1.3 Case study

The University of British Columbia (UBC), Point Gray campus in Vancouver was selected as a community for this study from a number of reasons. The term “community” in urban context was generally recognized as one that occupies certain geographical area, but unlike cities defined by specific size, communities are rather characterized by social networks (Huang et al., 2017b; Petersen, 2016). Communities share identity, have common interest and values and therefore planning and implementation of policies could be reached in a more meaningful manner. Examples include community-scale energy system planning incorporated with urban planning as response to climate change (Lin et al., 2017), or those using a risk-based methods (Ioannou et al., 2017) where community members are an important stakeholder. A variety of techno-economic parameters are also commonly used for evaluation of options (Ghafghazi et al., 2010; Arena et al., 2010) and energy planning for sustainable future (Bhowmik et al., 2017).

The Bioenergy Research and Demonstration Facility (BRDF) at UBC Vancouver campus is one of the most innovative and inspirational renewable energy developments recognized world-wide (UBC, 2015b). Built in 2012, this permitted biomass DES[8] is using the Nexterra gasification-combustion technology for CHP generation, to demonstrate the technology and to allow researchers to study emissions and their dispersion characteristics in a community setting among other projects. Wood waste, a mixture of forest residue and sawmill/planner waste is used as the fuel at the BRDF, supplied daily by Cloverdale Fuels Inc. (Cloverdale). Adding biomass to DH reportedly avoided 5,500 tonnes of fossil CO_2 which would have been otherwise emitted from natural gas combustion during the first year of operation (UBC, 2015c). Stack emissions are closely monitored and correlated to the quality of biomass feedstock and the local meteorological conditions. Since 2012 when it became operational, BRDF produced steam for approximately 20% of the campus's thermal energy demand of 1,011 TJ over the period 2012-2013 (Petrov et al., 2017). The rest was produced by combusting natural gas (base load) and #2 heating oil (peak load) at the UBC Power House (PH) built in 1925, which is gradually being replaced with the new Academic District Energy System (ADES), positioning "UBC as a Living Lab" with a more efficient hot water instead of steam heating system.

UBC Point Grey campus is a vibrant community of researchers, students, residents, employers and visitors with a pronounced daily and seasonal dynamics. It is continuously growing and new developments are providing more space and facilities for research and residency on its 4.02 km^2 property. Approximately 50,000 people daily work, reside or visit the campus, staying in more

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[8] Capacity: Thermal mode only 5.8 MW_{th}, 2.8 MW_{th} heat recovery and 1.96 MW_{el}.

than 500 buildings of different uses (offices, classrooms, laboratories, libraries, dormitories, etc). Some of the residences such as Marine Drive residential complex are located just across BRDF to the north and north-west. Due to such close proximity of residential buildings to a 20 m tall BRDF stack, both oxides of nitrogen and fine particle monitors were installed on the roof of Marine Drive building 5 to ensure acceptable levels of those pollutants at all times. Configuration and capacity of campus buildings (depicted as yellow rectangular surfaces), PH and BRDF as emissions sources considered in this study (depicted as red stars) are presented in Figure 1.3 and explained in detail in Chapter 3: and Chapter 4: of this study.

Figure 1.3 UBC campus buildings, BRDF and PH emission sources.
Source: UBC Campus + Community Planning.

A local weather station, Totem park station, is located to the south of BRDF and data on ambient temperature, humidity and wind parameters could be downloaded.

1.4 Thesis structure

The thesis is organized in chapters starting with the introduction chapter and the literature review chapter, followed by four chapters on research results, and a final chapter on overall conclusions drawn from the research work, limitations of the current study and opportunities for the further research. More specifically:

Chapter 2 provides a systematic literature review (detailed in Appendix A.1) with the goal to address the current scientific knowledge about three main topics covered in the subsequent chapters. Sections 2.1 to 2.3 cover biomass classification and characterization and control of resulting emissions in order to evaluate impacts of biomass-based district energy systems on local air quality and climate. Section 2.4 reviews existing literature addressing population exposure and associated health risks due to such exposure with a focus on inhalation intake fraction (iF) and health-related impact score (IS) metrics. Finally, subsection 2.5 recapitulates published results on global effects of biomass energy systems using life cycle assessment.

Chapter 3 is dedicated to developing an improved impact assessment methodological approach, with a focus on improving a dynamic iF method for assessments on local, community scale, environmental impacts (connecting local air quality and human health). The importance of introducing local and site-specific parameters for more accurate quantification of impacts is highlighted. The overarching goal of this chapter is to present a comprehensive methodological approach which could be generalized for assessing community-scale energy systems, while its application is demonstrated in subsequent chapter. Methodologies used for assessing the global issues are also covered.

Chapter 4 starts with a section describing a district heating system at the UBC Point Gray campus in Vancouver, BC, which was chosen as a case study. The subsequent two sections explain operational district heating scenarios considered in the study (section 4.3) and emission estimates and measurements in section 4.4. The second part of this chapter applies improved assessment approach (Chapter 3) and investigates in detail impacts of emitted pollutants from two operational plants, BRDF and PH, over five operational scenarios on local air quality (section 4.5) and human health (section 4.6). Where applicable, obtained result were compared with regulatory limits for emission sources and ambient air quality objectives.

Chapter 5 focuses on global impact assessment, in which three main DES operational scenarios were subjected to a streamlined life cycle analysis to quantify the global warming impact. Upstream processes for natural gas and heating oil as well as transportation, electricity and machinery operations were obtained via GHGenius and included in the analysis. Based on actual data on fossil fuel consumption at UBC and biomass feedstock locally supplied and gasified at BRDF, foreground information on energy and material flows as well as wastes generated were summarized and analyzed using two impact assessment approaches: 1) MS Excel for compiling emission inventories to evaluate impacts over different life cycle stages, and 2) SimaPro software with Ecoinvent database and IMPACT 2002+ for global impact analysis.

Chapter 6 tackles economic analysis as an important pillar of sustainability. Assessment of costs associated with the development, operation and maintenance of the UBCdistrict heating system is discussed along with the economics of GHG emissions. Externalities are also discussed.

Chapter 7 as the final thesis chapter summarizes findings of this study, outlines strengths and limitations and provides recommendations for future research work.

Chapter 2: Literature Review [9,10]

The current knowledge on DES with a focus on biomass as a feedstock was reviewed systematically to identify knowledge gaps in possible impacts, methods and approaches used for evaluating such impacts. Further details are provided in Appendix A1.

2.1 Biomass classification and characterization

Extensive investigation into biomass characterization and its potential for sustainable utilization for replacing fossil fuels and combating climate change have been reported in recent years. Generally, biomass could be generated either from natural processes (vegetation through photosynthesis, animal waste and food waste) or from processing of naturally obtained biomass such as municipal solids waste. According to Vassilev and collaborators (Vassilev et al., 2010), biomass could be classified as:

- Wood and woody biomass – which includes various wood species such as coniferous or deciduous, parts of a tree such as stem, branches, bark, but also various woody biomass forms such as pellets, briquettes, chips, sawdust;
- Herbaceous and agricultural biomass – grasses, straws and plant residues;
- Aquatic biomass – algae, seaweed, lake weed;
- Animal and human biomass waste – manures, chicken litter and others;

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[9] A version of this chapter was published. **Petrov, O**. (**2012**). Forest Residues to Energy: Is this a pathway towards healthier communities? National Collaborating Centre for Environmental Health. Evidence Review. Available from: http://www.ncceh.ca/sites/default/files/Forest_%20Residues_to_Energy_Mar_2012.pdf.

[10] A version of this chapter was published**. Petrov, O**., Bi, X., & Lau, A. (**2015**). Impact assessment of biomass-based district heating systems in densely populated communities. Part I: Dynamic intake fraction methodology. *Atmospheric Environment*, *115*, 70–78. https://doi.org/10.1016/j.atmosenv.2015.05.036**.**

- Industrial biomass waste – wastes from municipal works such as tree trimming, sewage sludge, demolition wood and others.

2.1.1 Chemical composition

Biomass is a heterogeneous mixture of organic and, to a lesser extent, inorganic matter known as ash. The chemical composition of biomass, especially the inorganic portion, varies due to high variation in moisture content, ash yield, and ultimately due to the biomass origins (Vassilev et al., 2010). Organic compounds are comprised of five main elements: carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). The major elements (>1.0%) are carbon (C), oxygen (O), hydrogen (H), nitrogen (N), calcium (Ca), and potassium (K). The minor elements (0.1-1.0%) commonly found in biomass are: silica (Si), magnesium (Mg), aluminum (Al), sulphur (S), iron (Fe), phosphorous (P), chlorine (Cl), sodium (Na) (Vassilev et al., 2010), as well as: cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), arsenic (As), mercury (Hg) and lead (Pb) (Telmo et al., 2010). The trace elements (<0.1%) are manganese (Mn) and titanium (Ti). Municipal wood waste could also be contaminated with a number of other elements. In order to be used as fuel, some of the main properties to be considered are:

2.1.2 Heating value

Structural analysis of biomass (main constituents: cellulose, hemicellulose and lignin) is important in estimating the higher heating value (HHV) through ultimate fuel analysis where the HHV of lignin is reported to be higher than HHV of cellulose and hemicellulose. HHV could be directly measured or estimated as (Vallios et al., 2009):

$$HHV = 34.1C + 123.9H - 9.85O + 6.3N + 19.1S \quad (2\text{-}1)$$

where: HHV is higher heating value in [MJ/kg]; C, H, O, N and S are carbon, hydrogen, oxygen, nitrogen and sulphur in [weight %]. Typical HHV values of different types of biomass are: green wood 8 MJ/kg, spruce wood 20.5 MJ/kg, softwoods 19.8 MJ/kg, hardwoods 19 MJ/kg, wood bark 20.3 MJ/kg, sawdust 18.4 MJ/kg (Saidur et al., 2011).

2.1.3 Moisture content

Moisture content is an important parameter as it directly impacts the combustion performance of biomass fuels. Ideal fuel would have low moisture content (Singh et al., 2017; Singh et al., 2014). While fresh wood may contain more than 50% of moisture (Striūgas et al., 2017; Zeng et al., 2017), pellet are typically between 5.1% and 8.5% moisture content for achieving high pellet density and strength (Huang et al., 2017).

2.1.4 Ash content

Ash content is indicative of the presence of inorganic and mineral compounds in biomass. It is one of the most studied biomass characteristics. The ash yield is the inorganic residue (formed from organic, inorganic and fluid components) resulting from the combustion process. Combustion temperature will have a substantial impact on total ash yield resulting in 20 -70% less ash for combustion temperatures above 1,000 ºC (Vassilev et al., 2010). High ash yields containing Cl, K, Na, P, S as well as other elements forming chlorides, sulphates, carbonates, oxalates, nitrates, to mention some, may cause issues during biomass thermochemical conversion (Vassilev et al., 2017). Furthermore, the composition of ash will depend on the biomass species and part of the biomass plant, with bark having higher ash content than wood (Saidur et al., 2011) .

2.2 Characterization and control of emissions from biomass-based energy systems

Conventional furnaces (such as cooking stoves) and open biomass burning (such as forest fires) emit particulate matters (PM) and a wide range of gaseous pollutants such as oxides of sulphur (SO_x), oxides of nitrogen (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), black carbon, free radicals and various organics (Naeher et al., 2007; Gustavsson et al., 2007). By comparison, advanced thermochemical conversion systems such as gasifiers are characterized by a reduction in the number of pollutant species and the concentration of PM, CO and volatile organic compounds (VOCs) (Sethuraman et al., 2011; Miranda et al., 2010). In addition, as previously mentioned, woody biomass is usually a heterogeneous fuel and emissions depend on the tree species and moisture content.

Boiler type and operating conditions, as well as the type of biomass, affect particulate and gaseous emissions (Kaivosoja et al., 2013; Kocbach Bølling et al., 2009; Boman et al., 2004; Boman et al., 2003). For example, when combusted in high efficiency boilers, wood chips (from forest residues and waste wood) emitted significantly higher fine particles with a diameter less than 2.5 microns ($PM_{2.5}$) and NO_x and SO_2 gases due to higher sulphur and nitrogen contents in wood chips. These emissions are higher than those emitted from the combustion of wood pellets. Sulphur content in wood pellets and wood chips ranges from 63.6 to 175 mg/kg dry wood, which is much lower than sulfur content in fossil fuels (Chandrasekaran et al., 2011).

The emission of gases and particulates in modern wood boilers is also lower than old-type residential boilers (Johansson et al., 2004). While the assumption of carbon neutrality of forest biomass is not correct (Röder et al., 2015; Vanhala et al., 2013; Holtsmark, 2013), fuel derived from woody biomass indeed has much lower greenhouse gas (GHG) emissions such as CO_2 and methane (CH_4) when compared to natural gas over the entire life cycle (Pa et al., 2011). Methane could be formed during biomass gasification/pyrolysis in the reducing zone, together with CO and H_2 (Sansaniwal et al., 2017) but is not directly released to the environment.

Air pollution control devices such as electrostatic precipitators (ESP) and selective catalytic reduction (SCR) need to be installed for the removal of particulates and NO_x, respectively. In general, air pollution control could be achieved using dry and wet methods. Dry cleaning methods do not use liquid but rather use gravity, centrifugal force, impaction, direct interception, electrostatic attraction and other mechanisms for pollutant removal. Examples of such controls for particle removal from flue gases are: cyclones, filters and ESPs. While cyclones are most efficient for coarse particles, ESPs and filters can achieve high removal efficiency over 99% for fine particles (Asadullah, 2014; Ghafghazi et al., 2011). Wet controls for particle removal include a large selection of scrubbers, wet ESPs and hybrid controls (Singh and Shukla, 2014; Ghafghazi et al., 2011). Wet methods, e.g. wet scrubbers, are also used for the removal of soluble gases via absorption in addition to adsorption. Some water soluble gases from biomass combustion are sulphur dioxide (SO_2), ammonia (NH_3), hydrochloric acid (HCl) and hydro-fluoric acid (HF) (Singh and Shukla, 2014).

2.3 Impacts on ambient air quality and climate

Maintaining good air quality is a challenge with population growth and industrial development. Even switching from fossil fuels to renewables needs to be evaluated beforehand to ensure maintaining air quality within prescribed limits and minimizing health risks. One study

(Jonsson and Hillring, 2006) found, based on dispersion modeling, that conversion to small scale district heating resulted in higher pollutant concentrations closest to the emission source (and then decreasing and spreading over a larger area), than the case of pellet stoves in individual houses. However, in both cases outdoor concentrations still remained within allowable air quality limits. The study, however, indicated that other factors may impact the dispersion of emitted pollutants and consequently ambient air quality (such as terrain, temperature inversion[11]). So contributing background pollutant levels and site-specific local emissions need to be investigated together.

As depicted in Figure 2.1, spatial and temporal scales of processes, which span eight orders of magnitude, exist in the atmosphere. Four main categories are:

- Microscale – which exists up to 100 m in space and minutes to hours in temporal scale; short-lived species such as free radicals and process are described by turbulent motions;
- Mesoscale – which exists on a spatial scale of tens to hundreds of kilometers where processes such as sea- and land-breezes, mountain-valley circulations dominate and oxides of sulphur, tropospheric ozone and aerosols;
- Synoptic scale – which is well known for the motion of weather systems over hundreds to thousands of kilometers and which is closely connected to the global scale, impact transport of moderately-lived (hours to years) species such as oxides of nitrogen,

[11] Temperature inversions are defined as an increase of ambient (i.e. outdoor) air temperatures with altitude which leads to stable atmospheric conditions and poor dispersion.

- Global scale – which is the largest spatial and temporal scale existing on a tens of thousands of kilometers where long-lived species such as methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), known as greenhouse gases (GHGs) and ozone depleting species exist for years.

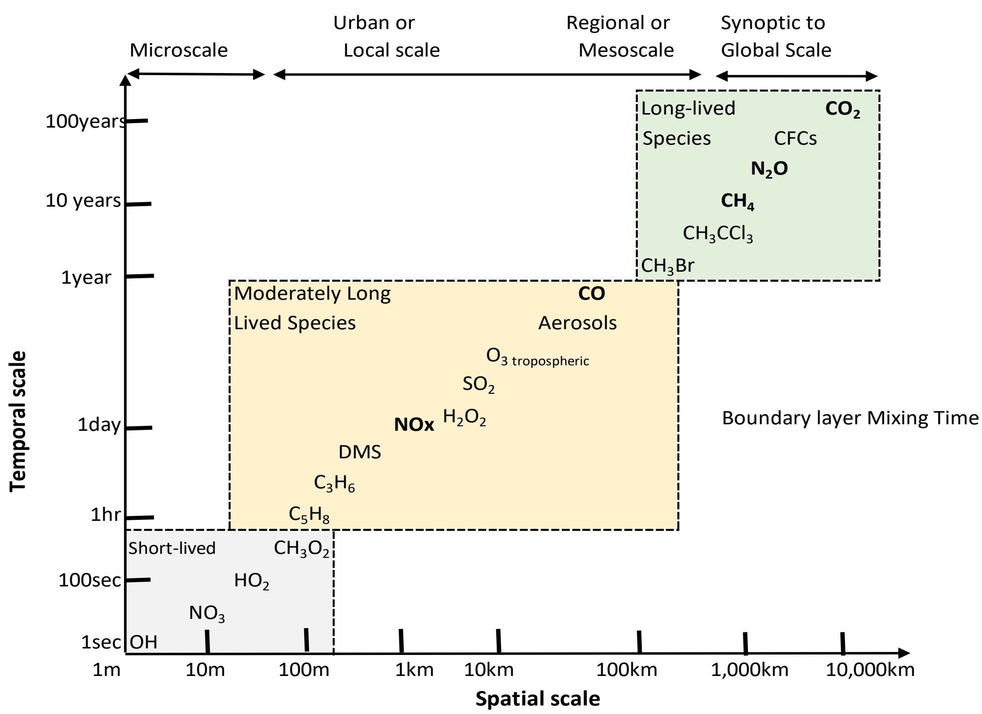

Figure 2.1 Atmospheric species on spatial and temporal scales.
Source: Based on Pandis and Seinfeld (2006).

These scales overlap so do the processes and species which undergo transport, chemical transformations and depositions after being emitted into the atmosphere. While short- and moderately-lived species determine the quality of outdoor (ambient) air on an urban/local scale, long-lived species have a profound impact on global scale, most notable of which is climate change and stratospheric ozone depletion (Pandis and Seinfeld, 2006). Among environmental issues, emissions of fine particles are recognized as ones very hard to predict as they will depend not only on biomass characteristics and operational conditions but also on local meteorology (Pantaleo et al., 2014).

2.4 Population exposure and health risks

Situated in communities, district energy systems (DES), even with renewable sources, can raise concerns about health risks for local populations especially with respect to fine $PM_{2.5}$ and NO_x levels (Genon et al., 2009; Jonsson and Hillring, 2006). Unlike conventional energy systems located in remote areas away from city centers, proximity of district energy systems can have direct impact on residents (Pa et al., 2011). Therefore, exposure scenarios in addition to emissions could help evaluate health risks of DES and compare them to conventional systems (Genon et al., 2009; Heath et al., 2006). Like in cases of conventional wood burning, Intake Fraction (iF) could be used as a metric for district heating systems to evaluate the inhaled portion of airborne pollutants by exposed populations (Ries et al., 2009).

For the assessment of air pollution and public health, inhalation intake fraction (iF), as the fraction of iF which encompasses three routes of exposure (inhalation, ingestion and dermal) should be used. Inhalation intake fraction is also called exposure efficiency (Evans et al., 2000; Lai et al., 2000; Smith, 1993), exposure effectiveness, nominal dose effectiveness (Smith, 1993) intake factor (Čupr et al., 2013) and inhalation transfer factor (Lai et al., 2000) by different authors, and it has been widely used as a key metric for evaluating population exposure to pollutants emitted from a source or source class including stationary (power plants), mobile (vehicular traffic) or other sources. In its simplest form it could be expressed as the incremental intake of a pollutant emitted from a source of interest and summed over exposed individuals of the studied population and exposure time, per unit of pollutant released from that source into the environment (Bennett et al., 2002). Inhalation intake is a product of airborne concentrations, population density at a location of exposure and breathing rate (Evans et al., 2002).

Inhalation iF has been used in evaluating impacts from different emission sources, such as urban smoke emissions in Canada (Ries et al., 2009), sulfur dioxide (SO_2), sulfate (SO_4), nitrogen oxides (NO_x), nitrate (NO_3) and fine primary particle ($PM_{2.5}$) emissions from industrial stacks in China (Wang et al., 2006; Zhou et al., 2006; Zhou et al., 2003), centralized and distributed electricity generation plants (Heath and Nazaroff, 2007; Heath et al., 2006) or other outdoor origins (Marshall et al., 2006) in the United States and Czech Republic (Čupr et al., 2013), proposed biomass plant in Italy (Curci et al., 2012), and non-reactive pollutants (Lobscheid et al., 2012; Du et al., 2012; Luo et al., 2010; Greco et al., 2007; Marshall et al., 2005a) or organics of particular concerns for human heath such as benzene from vehicular sources (Manneh et al., 2010; Loh et al., 2009). iF has also been used for exposure assessment associated with episodic exposures (Russo and Ezzat Khalifa, 2010; Nazaroff, 2008), or cooking in indoor micro-environments (Grieshop et al., 2011).

To estimate iF, a variety of approaches were applied on different spatial and temporal scales. Ambient pollutant concentrations were usually obtained by modeling, ranging from steady-state mass balance models (Manneh et al., 2010; Marshall et al., 2005b), to box models (Stevens et al., 2007a), and more sophisticated dispersion models such as ISC (Panepinto et al., 2014; Wang et al., 2006), AERMOD (Lobscheid et al., 2012), CALPUFF (Curci et al., 2012; Zhou et al., 2006; Zhou et al., 2003) and CMAQ (Xu et al., 2013) for stationary sources. Some authors (Zhou and

Levy, 2008; Greco et al., 2007) recommended higher spatial resolution dispersion models, especially for primary conserved pollutants such as $PM_{2.5}$ due to a significant near-source contribution, and because they can improve iF estimates and increase confidence in results (Manneh et al., 2010). Furthermore, many studies considered static and uniform population distribution based on either census tract population data or region and country average population data. One study (Marshall et al., 2006) introduced population stratified by age, income, ethnicity and 4 micro-environments for vehicular emissions exposure. In most of the reviewed studies using iF, breathing rate was 20 m^3/day for an adult during the day regardless the level of activities; only few studies, mostly dedicated to traffic exposures, introduced some kind of variation in breathing rates (Lobscheid et al., 2012; Luo et al., 2010; Loh et al., 2009). According to Wang et al. (2006), using a constant breathing rate of 20 m^3/day has long been recognized as a weakness of previous iF studies.

Intake fraction values vary by several orders of magnitude across reviewed studies. For stationary sources iF values for urban, rural, remote areas and ground-level, low and tall stack range from 0.1 to 44 ppm (Levy et al., 2002a) to 260 ppm for residents and 1000 ppm for pedestrians in a street canyon (Zhou and Levy, 2008). For a biomass-based DES located in densely populated urban areas, there is an expected high degree of variation in population, and possibly in micro-meteorological conditions which imposes extra challenges for accurate estimation of iF values. Summary of reviewed iF related studies is presented in Table 2.1.

Table 2.1 Summary of iF evaluation approaches based on the reviewed literature.

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates ($x10^{-6}$)	Reference
Point source(s)/energy related studies					
Forecasted the temporal and spatial distribution of PM_{10} pollution from 3 main sources in Taiyuan City, China	(BPANN) model 33 x 16 grids; each grid 500m x 500m PM monitoring data Yearly average data	Data from city's records 2002-2008 Yearly average population per km^2 used as pop. density temporal resolution	Constant breathing rate of an adult 20 m^3/day	mean = 8.5 in urban area mean = 4.61 in suburbs	Zhang et al., 2013
Characterization of properties of 6 size fractions of PM(focus on PAHs) an assessment of the human health risks they pose [Brno, Czech Republic]	PM Sampling followed by mineralogical and chemical analyses	Exposure scenario, a person body weight 70kg, exposure 8hr/day for 70 years	Constant breathing rate of an adult 20 m^3/day	IF > 1.5 (Statistically significant genotoxic potential, GP) for PM < 0.45µm and 0.95 µm>PM>0.4 µm for 30m^3/ml When IF expressed per mg of PM and associated PAHs, then the highest GP is for PM in range 1.5-3 µm;0.95-1.5 µm and 0.45-0.95 µm	Čupr et al., 2013
Intake *avoided* per unit of SO_2 emissions *reduced;* Beijing-Tianjin-Hebei region, China	CMAQ modeling system	Population of 35 sub-areas obtained from provincial statistical yearbooks	Constant breathing rate of an adult 20 m^3/day	<u>Avoided iF per tonne of SO_2</u> Heat & electricity 0.473 Smelting 0.646 Other 0.934	Xu et al., 2013
Impact of SO_2 ,NO_2 and PM_{10} emissions from a proposed biomass energy power plant, Italy	CALPUFF dispersion model; Domain 40 km×40 km, 250 m resolution, 8 vertical layers	City population of 70,000 people	Constant breathing rate of an adult 20 m^3/day	Max predicted for SO_2 and PM_{10} ≈ 25	Curci et al., 2012
Integration of PM-related emissions and PM human exposure into LCA – microenvironments: outdoor (urban, rural & remote), and indoor	Source-location framework; 3 emission heights in different microenvironments; regression models from literature	Based on average population density for urban, rural, remote areas	13 m^3/day	For primary $PM_{2.5}$ <u>Stack urban rural remote</u> High 11 1.6 0.1 Low 15 2.0 0.1 Ground 44 3.8 0.1 Emission 26 2.6 0.1 Weighted average	Humbert et al., 2011

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates (x10^{-6})	Reference
For 32 substances (8 relevant to inhalation iF), evaluation of spatial iF variation within and across the 3 levels of regionalization (LCA),Canada	Steady-state mass balance equation 3 spatial resolutions: 15 eco-zones, 13 provinces, and 172 sub-watersheds all with 537 air regions with the same mixing layer and world-level (box model) compartment	varying	n/a	The highest intake is for long-range transport chemicals and is driven via intake by world-level spatial compartment due to large population For low persistent chemicals higher resolution needed in LCA to capture population density variations	Manneh et al., 2010
iF of winter urban wood smoke - concentration of $PM_{2.5}$ and levoglucosan , Canada	Mobile monitoring LUR Winter daytime, winter nighttime and shoulder heating season fall/spring	Aggregate and census tract population data, 2001 Census Canada	Commonly used BR adjusted ±20% for day/night	Geom. mean/geom. SD $PM_{2.5}$ 13 (1.9; 6.6 -24) Levoglucosan 15 (3.3; 4.5-50)	Ries et al., 2009
NO_x , $PM_{2.5}$ and CH_2O Compare California's 25 existing large scale central power stations (CS) and 11 hypothetical distributed electricity generation (DG) plants	Gaussian plume modelling system	Year 2000 census tract-level population data, no temporal variability	12 m^3/day	Median: CS DG NO_x 0.66 11 $PM_{2.5}$ 0.78 16 CH_2O 0.66 13	Heath and Nazaroff, 2007
				Conserved Primary pollutants 0.8 16	Heath et al., 2006
Evaluate impacts of emission source location on population exposure in terms of PM and SO_2 emissions; 29 plants in China	CALPUFF dispersion model	1999 country-level population data	Constant breathing rate of an adult 20 m^3/day	Primary $PM_{2.5}$ 10 average SO_2 5 average Sulfate 4 average Nitrate 4 average	Zhou et al., 2006

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates ($x10^{-6}$)	Reference
Inhalation iF of 5 air pollutants of outdoor origin; California's South Coast air Basin	CAMx Eulerian photochemical air pollution model; Resolution – hourly values in 2x2km grid cells in a 210x120km domain	~25,000 individuals, stratified by age, income, ethnicity Time-location activity survey data 4 microenvironments: outdoor, indoor &residence, indoor and non-residence, in/near motor vehicles	Age-, gender- and activity – specific; Calculated average to be 13.1 m^3/day	Inhalation intake rate: Diesel $PM_{2.5}$ 47 µg/day Variation in intake rates from 4 -19% when varying parameters (BR, mobility, location, all parameters)	Marshall et al., 2006
SO_2 and total suspended particles (TSP) iF emitted by 590 stacks of 4 industries, China	Industrial Source Complex Long Term (ISTLT3) model Within 50 km	1kmx1km grid- densely populated areas; Country-level pop. data for industrial - rural areas	20 m^3/day Sensitivity analysis with 12, 15 and 17 m^3/day	SO_2 4.2 ± 9.16 average TSP 4.4 ± 8.15 average	Wang et al., 2006
Seasonal iF for emissions of sulfur dioxide (SO_2), sulfate (SO_4), nitrogen oxides (NO_x), nitrate (NO_3) and fine primary particles (primary $PM_{2.5}$). power plant, China	CALPUFF dispersion model; 3360 km × 3360 km domain with grid spacing of 28 km and 120 receptors	County-level population data for the year 1999; ArcGIS was used to match population data with the concentration data	Constant breathing rate of an adult 20 m^3/day	Feb. May Aug. Nov. SO_2 13 5 8 8 SO_4 11 3 6 4 NO_3 15 2 2 7 $PM_{2.5}$ 25 9 13 14	Zhou et al., 2003
A regression-based model for iF of primary and secondary PM(LCIA) 40 coal-fired Power plants	Based on the case study prepared by Wolff who used CALPUFF model of domain 100 k x100 km	1999 data; Estimate of total population within a fixed radius from the source	As per case study (n/a)	Mean Primary $PM_{2.5}$ 2.2 Mean secondary sulfate 0.2 Mean secondary nitrate 0 .035 Primary $PM_{2.5}$ -- iF greater for power plants with lower stacks, lower near-stack mixing height, higher near-source population	Levy et al., 2002b
Traffic related studies					
IF of non-reactive constituents of motor vehicle exhaust, China	Monitoring data of carbon monoxide	Government census data for 1996, 2001 and 2006 interpolated to	12.5 – 20.5 m^3/day depending on age groups	Average annual 270 For children and adults, exposure to motor vehicle emissions outdoors	Luo et al., 2010

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates ($x10^{-6}$)	Reference
		allocate population to different age groups	and 4 micro – environ.	in/near vehicles is comparable with indoor exposures	
iF of primary conserved air pollutants from on-road vehicles, US	AERMOD steady-state plume model; 50 km of the centroid of the source census block	Census-tract spatially variable to include: county, state and national levels	Long term average 14 m^3/day	Pop. weighted mean = 8.6 Pop. weighted median = 3.6 to 5.1 For census regions Pop. weighted med = 2.2 to 7.5 Urban areas = 14 average Rural areas =9 average	Lobscheid et al., 2012
iF of NO_x and, $PM_{2.5}$ emissions from vehicles, China	24-hr personal exposure sampling for 114 individuals and concentration monitoring in urban area of Beijing	3 microenvironments (traffic, work, home) for adult and children population groups Data from Beijing Statistics Bureau 2008	0.35 - 2.85 m^3/hr based for 3 micro environments for adults and children	(0.0171±x 0.0124)$x10^{-3}$ ppm [$PM_{2.5}$] for an individual over 24 hr; (0.0136±0.0087) $x10^{-3}$ ppm for children – average; (0.0199±0.0143) $x10^{-3}$ ppm for adults – average; Total children popul. = 18 ±11ppm Total adults popul. = 135±96 ppm	Du et al., 2012
Spatial and population-based iF for vehicular benzene emissions, Finland	3 methods: EXPAND modelling approach (traffic planning model EMME/2, emission modelling CAR_FMI, streets poll. Model OSPM); Personal monitoring; Box model	From EXPOLIS project. 4 activities; Average population in the area	1 m^3/hr constant rate (for EXPOLIS) and for EXPAND modeling used different BR depending on micro-environm.	EXPAND: annual mean = 10 Monitoring: Median = 30; Mean=39 Box model: Median = 4; Mean=7 Average=0.01 from measured data for 48-hr	Loh et al., 2009
Evaluation of iF of fine particles $PM_{2.5}$ from sources (6 categories) in Europe and Finland	The regional-scale dispersion model SILAM. 2 geographical domains- Europe and Northern Europe; Spatial resolution 5 km and 30 km	Finland, population data 2004 with resolution 250 x 250m; EU countries, EEA database, 100x100m (2001); Non-EU countries, CIESIN, 2-4km (2000)	Constant breathing rate of an adult 20 m^3/day	Europe 0.31- 4.42 Finland – traffic 0.68 (the lowest iF for power plants, 0.5) Winter iF > other seasons Summer iF < other seasons iF is 1.3 times larger for smaller spatial resolution	Tainio et al., 2009

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates (x10^{-6})	Reference
Exposure of residents to seasonal and annual average $PM_{2.5}$ and elemental carbon (EC) from diesel trucks, Long Beach, UC	CALINE4 line source model	Census block, block group and parcel, year 2000 - to evaluate the influence of different spatial resolutions on estimated population exposure	Constant breathing rate of an adult 20 m^3/day	$PM_{2.5}$ Average 14 (range 10 - 22) iF in winter is 1.4 times higher than in summer iF of streets traffic is 1.4 times higher than those of freeways traffic	Wu et al., 2009
Evaluates the impact of street canyons (median building heights) to primary conservative and reactive pollutants from traffic, NY, US	OSPM model	Residents, workers, pedestrians US census data (2000) LANL 250m raster – daytime and nighttime population CHAD, ACS databases	12-38 m^3/day depending on population category; does not differentiate BR day vs night	$PM_{2.5}$ Pedestrians ~ 1000 Residents 260 Total iF 2200 PM_{10} Pedestrians ~ 1000 Residents 150 Total iF 1700	Zhou and Levy, 2008
Evaluation of primary and secondary PM iFs for Mexico City using 5 different methods	-Box models -Atm. dispersion complex model -Emission inventory – PM composition model -Regression analysis	Population census data, 2000	Constant breathing rate of an adult 20 m^3/day	Factor-of-five in variability of iF among different methods	Stevens et al., 2007a; Stevens et al., 2007b
Evaluates the spatial extent of mobile source iF - four mobile source iFs for primary and secondary $PM_{2.5}$ in 3080 US counties/national	Source-receptor matrix (regression model) based on Climatological Regional Dispersion Model (CRDM)	1990 Census data (Sensitivity analysis for 2000 Census data) County-level data	Constant breathing rate of an adult 20 m^3/day	Primary PM2.5 0.2– 25 (median=1.2; mean= 1.6) The average across the US = 2.5 The median iF of Secondary sulfates is a factor of 6 greater than the median iF secondary nitrates	Greco et al., 2007
iF for non-reactive vehicle emissions in US urban areas	One-compartment steady-state mass balance model Emission-to-concentration relationship Analyzing US NATA	2002 population and area data; linear population density	12.2 m^3/day based on metabolic activity	Population-weighted mean varies from	Marshall et al., 2005b
Impacts of urban population density and	Single compartment model - concentrations	Spatial variation of population density	n/a4.4 (NATA data) to 21 (one-	Smaller-sized areas tend to decrease vehicle emissions while increase	Marshall et al., 2005a

iF Study Goal/Scope	Pollutant Concentration Calculation Method	Population Density Method	Breathing Rate	IF estimates (x10^{-6})	Reference
land area changes on per capita inhalation intake of primary pollutants from vehicles	are uniform throughout the area		compartment model	per capita intake; urban sprawl tends to increase vehicle emissions but to reduce per capita intake;	
iF for carbon monoxide (CO) and C_6H_6 from vehicles California South Coast Air Basin, US	Ambient monitoring data, period 1996-1999	The average population density of 860/km^2 Census US 2001	12.2 m^3/day based on metabolic activity	CO 32; C_6H_6 36	Marshall et al., 2003
Indoor exposure related studies					
Cook stove replacement options ($PM_{2.5}$)	Use available exposure and emission data	Exposed individual	7.8 m^3/day assumed for children and female adults	Median 0.18 If are 6 times lower in houses with a chimney than without a chimney	Grieshop et al., 2011
Individual iF of PM generated in kitchens	Measurements to determine the size dependant emission rate; Computational fluid dynamics (CFD) modeling	Individual exposure	Air ventilation rates 518.4 m^3/hr	High exposure to PM even when exhaust hood used as intervention to remove PM	Gao et al., 2013
iF of a seated person in the office 2.6m x 2.5m x1.7m with multiple contaminants	CFD model under different ventilation and temperature regimes	Individual exposure Computer simulated person	-	Personal ventilation system reduces iF by an order of magnitude, body T changes little effect on iF	Russo and Ezzat Khalifa, 2010

Assessment of exposure to airborne pollutants is an essential component of human health risk assessment (HRA) (World Health Organization, 2014). Pollutant concentrations could be either measured or modeled (Branco et al., 2014; Gulliver and Briggs, 2011), and exposure evaluated in conjunction with population activity (Gerharz et al., 2013). Relatively recently developed methods using remote sensing, land use regression modeling (Lee et al., 2017; Dirgawati et al., 2016; Knibbs et al., 2014), or combined methods (de Hoogh et al., 2014) improved HRA. Risk assessment can also utilize iF instead of pollutant concentrations (Ji et al., 2011). Subsequently health risks could be estimated by population-weighted health-risk-based air quality index (Shen et al., 2017), or human health-related impact score IS (Jolliet and Fantke, 2015).

2.5 Carbon footprint and large scale impacts of district energy systems

Fossil fuels used for energy production are seen by scientists as the main source of GHG emissions so their replacement with cleaner and renewable energy sources is a world-wide policy approach. Among renewables, biomass is an attractive choice perceived as a natural carbon sink due to CO_2 uptake by trees, a natural process known as carbon fixation (IEA, 2002). However, the replacement of fossil fuels by biomass may not be a simple-minded solution as CO_2 balances depend on many factors such as: a fossil fuel energy system being replaced versus a technology used for biomass conversion indicating the dependence of GHG emissions on the system efficiency (Schlamadinger and Marland, 1996; Schlamadinger et al., 1995). Moreover, forest growth rates and project time perspectives could be important factors influencing the overall net CO_2 emissions which would be lower in case of long-term projects and high-efficiency of wood fuels substitution compared to just storing carbon in standing trees (Schlamadinger and Marland, 1996). On the other hand, associated costs (Repo et al., 2015;

Levihn, 2014) and sustainability of bioenergy determined mainly by the biomass type and growing location (Evans et al., 2010) could be foreseen barriers to consideration of bioenergy as a viable replacement alternative for fossil fuels.

2.5.1 Bioenergy and carbon neutrality discussions

The notion of carbon neutrality of bioenergy arose from the fact that carbon emitted to the atmosphere as a result of biomass burning would be offset by trees via absorption of CO_2 but that may lead to an error in accounting for carbon-based emissions (Haberl et al., 2012). One of the reasons lies in missing to account for carbon uptake by plants which could have occurred had those plants not been harvested at all (Cambero and Sowlati, 2014), or not accounting for carbon loss due to harvesting of available residues (Repo et al., 2015).

Carbon neutrality of biomass is widely used in literature with a very broad meaning (WBCSD, 2015) such as "life-cycle neutral biomass" representing long-term stored atmospheric carbon which is equal to or greater than emissions associated with the use of such biomass over the entire life cycle. Similarly, "carbon-cycle neutral biomass" refers to biomass for which estimated emissions of biogenic carbon to the atmosphere are completely offset by new growth. Reviewed literature suggested inaccuracy of the immediate assumption of forest biomass carbon neutrality (Röder et al., 2015; McKechnie et al., 2011), as it is a time dependent parameter since forest carbon stocks or sinks, such as soil carbon stocks, could be reduced over time (Vanhala et al., 2013; Holtsmark, 2013). In case of wood residues, forest carbon stocks would not be impacted if the rate of harvesting (carbon removal) is equal to the rate of residue decomposition (in case residues were not removed) (McKechnie et al., 2011). Hektor et al. (2016), suggested that assessing carbon neutrality should be performed on the actual case values since the outcome, i.e. CO_2 emissions, will largely depend on factors such as: whether biomass originates from sustainably managed forests, biomass characteristics such as moisture content, and applied conversion technologies, all of which can lead to biomass being characterized as both carbon and climate neutral. Another recently published analysis (Nabuurs et al., 2017), which considered realistic case of European sustainably managed forests, pointed out that the use of woody biomass for energy did not reduce large scale average forest carbon stocks but caution should be taken for future estimates due to possible natural disturbances. Among all, carbon debt for removal of harvested residues is the fastest one to be compensated, within a decade. Appendix A.2 summarizes reviewed studies on carbon neutrality.

2.5.2 GHG emission estimates

A comprehensive evaluation of bioenergy benefits with respect to GHG emission reductions should entail emissions evaluation across the entire biomass supply chain, including GHG balance and carbon sinks estimates (van Dam et al., 2010) for carbon footprint calculations (Levihn, 2014). Processes such as biomass recovery and removal require energy so such processes contribute to CO_2 emissions (Gustavsson et al., 2011). Furthermore, there are some emissions related to biomass storage so neglecting that fact GHG savings, utilizing forest biomass in combined heat and power (CHP) and heat production only could be over-rated and be as high as 98% (Jäppinen et al., 2014). Harvesting scenarios are another parameter causing calculated carbon footprint for wood products to vary widely (Newell and Vos, 2012). It is worth noting that in comparison to fossil fuels such as coal, GHG emissions reduction of 83% could be achieved if wood pellets are used instead (Röder et al., 2015). This is especially true for a long-time horizon such as a 100-year period when a significant decrease of 41 Mt of CO_{2eq} was estimated by a study considering wood pellets replacing coal (McKechnie et al., 2014). However, when accounting for storage emissions, dry matter losses in the supply chain or other biomass-related emissions, it may turn out that pellet co-firing or large-scale biomass electricity generation exceed GHG emissions compared to coal-fired electricity generation, when storage exceeds the period of 4 months (Röder et al., 2015). More specifically, this study claims that still is little known about methane emissions from wood stockpiles and recent studies came out with a large range of results for CH_4 emissions, from negligible to over 60%. Drying options also highly influence GHG emissions when fossil fuels are used instead of biomass as a drying fuel.

The importance of biomass feedstock choices is emphasized by a study focusing on climate change mitigation options (Giuntoli et al., 2015). While current CO_2-approach is widely used in biomass-related LCA studies for global warming assessments, the authors demonstrated that the impact of bioenergy could be assessed by other parameters such as surface temperature changes and other climate forces. The study concludes that the rate of surface temperature increase by the end of the century as a result of biomass use will depend on the decay rate of the residues used among other parameters. Long-term bioenergy production from a slow-decaying wood will not contribute to climate change mitigation compared to natural gas, unless the biomass residues with the decay rate above 2.7% per year are chosen as feedstock for energy (heat) production. Overall, as for the first decade of CO_2 emissions, similar impacts from biomass and fossil fuels could be noticed but CO_2 emitted from bioenergy use stabilizes over time (Cherubini et al., 2013).

Chapter 3: Integrated impact assessment approach to evaluate community-based district heating systems[12]

3.1 Introduction

Systematic review of the literature indicated knowledge gaps in proper environmental assessment of growing community-based district energy systems. There is a need for improving current methods for adequately evaluating impacts of DES at a much smaller spatial and temporal scale than it was commonly used for large, remote power plants.

Impact assessment must therefore integrate different methods: ones that can adequately and more accurately address process impacts on local temporal and spatial scale (short-term local air quality and immediate community exposure) and methods adequate for addressing impacts on large spatial and temporal scale such as climate change (IPCC 5th Report, 2015) and overall human health. Thus, approaches used to design, propose, justify and apply a comprehensive state-of-the-art methodology for evaluating biomass-based district energy systems in a community setting are presented in this chapter. In addition to explaining micro-climatological characteristics and their importance for the pollutant dispersion close to a pollution source, local impact assessment method uses data for only one (BRDF boiler) stack with an electrostatic precipitator (ESP) for particle control, and one type of pollutant, particulate matter with diameter less than 2.5 micrometers ($PM_{2.5}$), over a period of one month to investigate the effect of

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[12] A version of this chapter was published. **Petrov, O.**, Bi, X., & Lau, A. (**2015**). Impact assessment of biomass-based district heating systems in densely populated communities. Part I: Dynamic intake fraction methodology. *Atmospheric Environment, 115*, 70–78. https://doi.org/10.1016/j.atmosenv.2015.05.036.

dynamic variations of population and micrometeorological conditions on iF. One month data are found to be representative for the purpose of the method development as it takes into account 720 hours of measured wind data from a local surface weather station in addition to modeled prognostic meteorological data MM5 (Fifth-Generation Penn State/NCAR Mesoscale Model), actual plant operating parameters and actual campus population data. Methods presented in this chapter provide foundation for integrated impact assessment of the Bioenergy Research and Demonstration Facility (BRDF) selected as a case study and carried out in subsequent thesis chapters.

3.2 Methods

This research study utilized quantitative research methods. Methodologies utilized included:

- Collecting and analyzing secondary data from the records available at PH and BRDF, professional reports prepared for both plants, permit for BRDF, GIS-based campus planning data for building use, occupancy, building locations and dimensions;
- Collecting and analyzing local meteorological data to determine the impacts of locally induced circulation patterns important in the dispersion of pollutants;
- Site visits data collection and data processing for an in-house district heating life cycle inventory database;
- Improving methodological approach for assessing the impact of community-based DES by introducing site-specific parameters and applying mathematical modeling and mapping, as well as using dispersion and GIS software packages such as WRPLOT View™, CALPUFF View™ and ArcGIS 10.1;
- Statistical analysis of data with inclusion of uncertainties of data.

3.3 Local air quality assessment methodology

3.3.1. Microclimatic conditions and diurnal circulation patterns

With emission sources being located in close proximity to people, local microclimatic diurnal variations play a pivotal role in accurate evaluation of population exposure. Coupled with diurnal population density dynamics, local air circulation patterns could result in different exposure patterns and consequently different iF during day and night. Coastal areas, such as the UBC Vancouver campus which is located on the Pacific coast and surrounded by the Pacific Spirit Regional Park, are subject to pronounced diurnal variations in wind patterns due to different heating capacities of land and water (Trenberth and Stepaniak, 2004) resulting in wind mostly blowing from the ocean towards land (sea breeze) during the day and from land towards the ocean (land breeze) at night. Such microclimatic conditions as well as their impacts on in-land and orographically induced circulation patterns were well documented in the literature (Fock and Schlünzen, 2012; Azorin-Molina et al., 2011; Buckley and Kurzeja, 1997; Lu and Turco, 1994).

One year daytime and nighttime wind data from six Metro Vancouver surface monitoring stations (Doerksen, 2012) were analyzed to demonstrate differences in day and night wind patterns and impacts of orographic features which cause upslope (daytime) and downslope (nighttime) circulation. As presented in Figure 3.1, stations located at the coastline, Horseshoe Bay (T35) and Vancouver International Airport (YVR) (T31), are characterized with prevalent land-breeze circulation during nighttime and sea-breeze circulation during daytime periods.

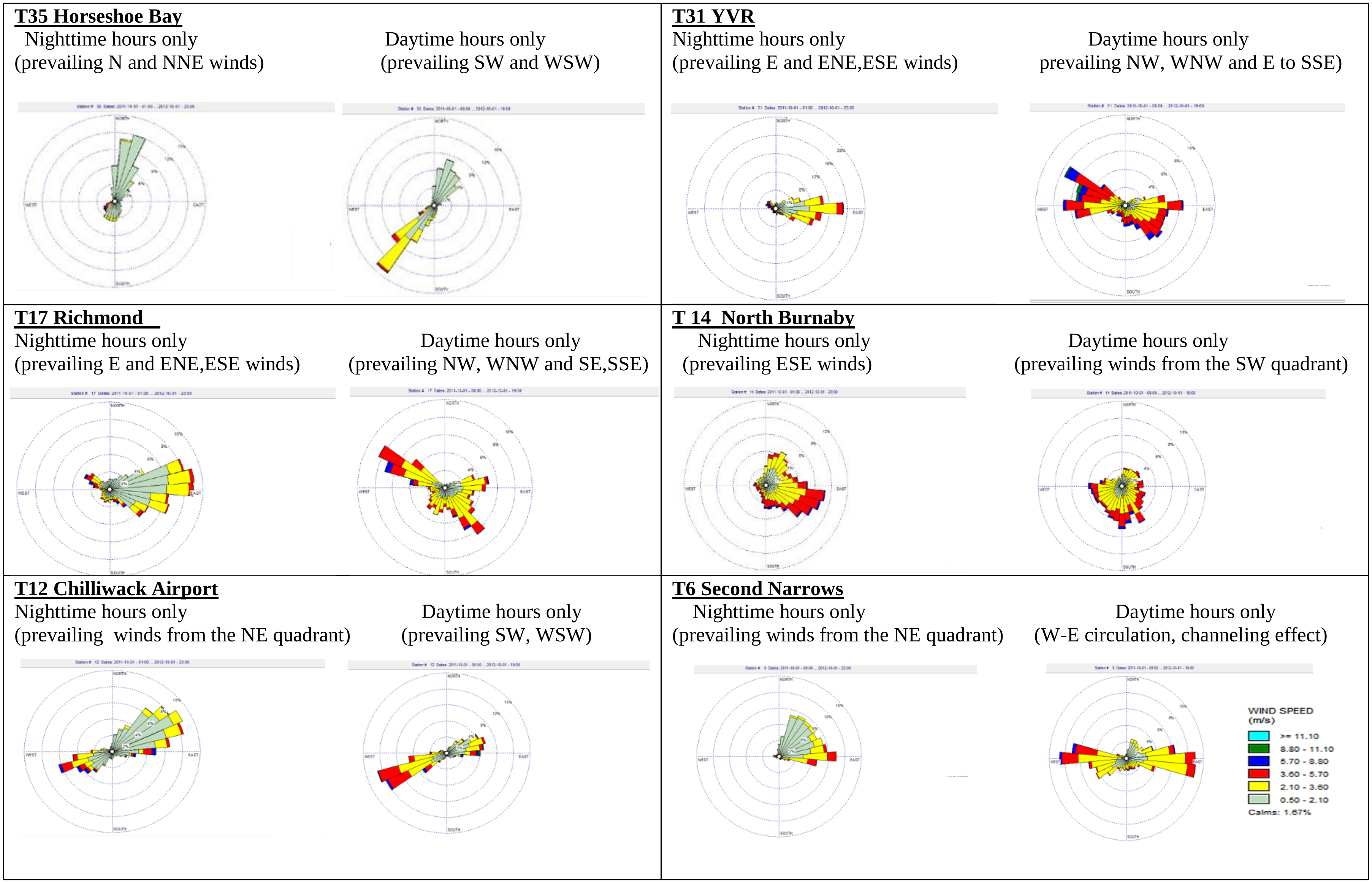

Figure 3.1 Wind patterns for day and night periods at selected Metro Vancouver stations.

Other stations located at some distance from the shore, Chilliwack Airport (T12), Richmond South (T17), and North Burnaby (T14) at Simon Fraser University (SFU) located at the elevation of 360 m above the sea level, also demonstrated pronounced differences in day and night wind patterns. Second Narrow station (T6) shows the channeling effects caused by daytime circulation influenced by narrow Burrard Inlet situated between mountainous north shore and mainland Vancouver while mountain breeze dominates nighttime circulation.

One month of wind data from the UBC Totem weather station were analyzed to investigate prevailing winds in terms of day-night characteristic wind patterns as hypothesized due to the unique campus location. Wind roses (Figure 3.2) were prepared for a total of 360 daytime hours (8 am to 7 pm) and 360 nighttime hours (8 pm to 7 am) for September 2012 using WRPLOT View™ software from Lakes Environmental (Lakes Environmental, 2012a).

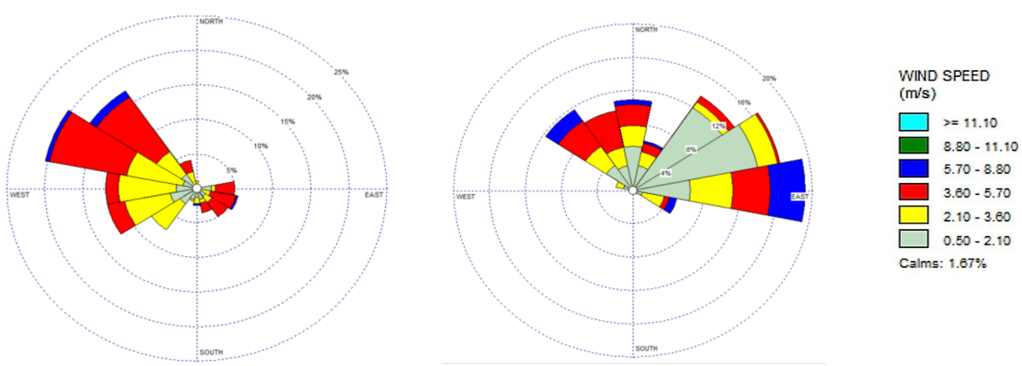

Figure 3.2 Wind rose for daytime (left) and nighttime (right), September 2012, UBC Totem weather station.

Over 77% of daytime hours winds were blowing from the ocean, with prevailing winds 20.3% of time from WNW (west-northwest), 16.9% of time from NW (northwest), and 11.9% of time from each W (west) and WSW (west-southwest) directions.[13] Only 20.6% of daytime hours wind was blowing from the north-east quadrant, i.e. from land towards the ocean. Calms comprised less than 2% of daytime hours. Nighttime circulation patterns showed the opposite trend. While 71.3% of nighttime hours winds were blowing from land towards the ocean, predominantly from east (E), east-northeast (ENE) and northeast (NE), with 19%, 16.5% and 13.5% of total nighttime hours respectively, winds coming from the ocean (the north-west quadrant) were recorded only 23.9% of time. During nighttime, calms were recorded for 3.9% of time. Following the results of this analysis, modeling scenarios were designed to incorporate diurnal wind circulation dynamics to evaluate its effects on iF estimates.

3.3.2. Dispersion modeling: CALPUFF modeling system

Dispersion modeling is a convenient approach to evaluate ambient concentrations of emitted pollutants from a source or multiple sources for a variety of purposes. It is becoming a crucial tool in decision-making processes about population exposure, health impacts and environmental justice (Borrego et al., 2015; Maroko, 2012). This method is commonly used for planned pollution sources to evaluate potential impacts before facility construction (Vallero, 2014), for modification of existing sources (Todorovic et al., 2015), for evaluating atmospheric fate of a particular pollutant (Holmes and Morawska, 2006) including model validation with observational data (Abril et al., 2016), for urban scale modeling (Pepe et al., 2016) or near-field modeling in urban areas (Tominaga and Stathopoulos, 2016).

[13] Wind direction is in meteorology defined as the direction wind is blowing from; eg. “Northerly winds” implies that wind is blowing from north towards south.

CALPUFF View™, version 6.4 (Lakes Environmental, 2012b), a multilayer, non-steady-state Lagrangian Gaussian puff dispersion model, was used in this study to estimate ambient concentrations at different receptors on campus. It is a preferred and verified regulatory model in the United States (US EPA: SCRAM, 2015) and BC (BC MoE, 2015; BC MoE, 2008). CALPUFF has the capability to cover a large spatial domain with a high resolution to capture microclimatic and atmospheric characteristics conducive to dispersion (Greco et al., 2007), particularly important in urban areas with non-homogenous conditions (Fisher et al., 2005). CALPUFF is suitable for cases of complex terrain and coastal circulation effects and it has previously been used in iF studies (Curci et al., 2012; Zhou et al., 2006; Zhou et al., 2003; (Jonathan I Levy et al., 2002).

The basic equation for a puff model that connects emitted pollutants with the ambient concentration at a receptor (Scire et al., 2000; Schnelle and Dey, 2000) is:

$$C = \frac{Q}{2\pi\,\sigma_x\sigma_y}\; g \exp\left[-d_a^2/(2\sigma_x^2)\right]\,\exp\left[-d_c^2/(2\sigma_y^2)\right] \qquad (3\text{-}1)$$

With "g" being expressed as:

$$g = \frac{2}{(2\pi)^{1/2}}\sum_{n=-\infty}^{\infty}\exp\left[-(H_e + 2nh)^2/(2\sigma_z^2)\right] \qquad (3\text{-}2)$$

Where:

C is the ground-level pollutant concentration [g/m^3] per the distance [m] traveled by the puff,

Q is the mass of the pollutant in the puff [g],

σ_x is the standard deviation of the Gaussian distribution in the down-wind direction [m],

σ_y is the standard deviation of the Gaussian distribution in the cross-wind direction [m],

σ_z is the standard deviation of the Gaussian distribution in the vertical direction [m],

d_c is the distance from the puff center to the receptor in the cross-wind direction [m],
g is the vertical term in the Gaussian equation [m],
H_e is the effective height above the ground of the puff center [m], and
h is the mixing-layer height [m].

Major CALPUFF features include: possibility of modeling constant or variable emissions for all types of sources (point, volume, area, line); gridded 3-D meteorological fields, vertically and horizontally-varying turbulence and dispersion rates, rural and urban, stability-dependent dispersion coefficients, building downwash effects, plume rise, dry deposition and wet removal, chemical transformation options etc.

The main components of the CALPUFF modeling system in addition to a large number of preprocessing programs are:

1. CALMET – a meteorological program which develops wind and temperature fields within a three-dimensional modeling domain;
2. CALPUFF – a model which simulates dispersion of emissions as "puffs" based on spatial and temporal variation of generated meteorological fields by CALMET, producing hourly concentrations or hourly deposition fluxes at selected receptors;
3. CALPOST – processes obtained data, produces tables and identifies the highest and second highest concentrations, produces graphical representations of results such as contours, lines connecting locations with the same values of pollutants.

Modeling domain in an initial run was selected to cover an area of 2.6 km x 4 km around the emission source, BRDF boiler stack (EN 02), which was selected to be a reference point for modeling. The domain extended 2 km in each of directions to the north, south and east from the plant and only 0.6 km to the coast at the west (toward the ocean). The selected domain (Figure 3.3) ensured coverage of required receptors (campus buildings) without producing output pollutant concentrations over the ocean since population located on campus was the subject of this analysis.

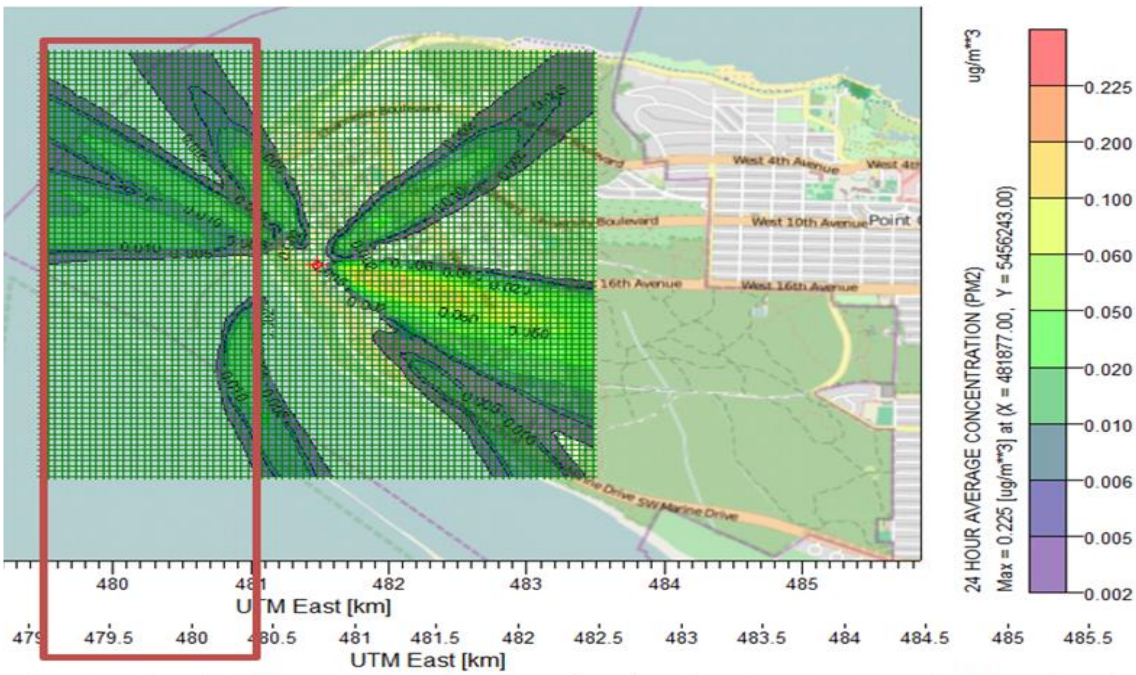

Figure 3.3 Nested grid receptors, red rectangular depicts an area with removed receptors due to absence of population.

3.3.2.1. Model input data

CALPUFF modeling system (specifically, CALMET processor) requires the following meteorological data input: hourly surface observation of wind speed and direction, temperature, cloud cover, ceiling height, surface pressure, relative humidity and precipitation (optional). Meteorological input consisted of one hour prognostic MM5 (Fifth-Generation Penn State/NCAR Mesoscale Model) data for 2012 – 2013 prepared by Lakes Environmental, with 50 km x 50 km coverage, 4 km resolution and 11 vertical layers. This initial modeling scenario was carried out only for September 2012. Meteorological grid for CALMET was set at 12.5 km x 12.5 km with 250 m spacing. In addition, data from stations presented in Table 3.1 were analyzed for supplementary entries.

Table 3.1 Surface and upper-air weather stations considered in the study.

STATION NAME	STATION ID	CITY	STREET ADDRESS	Latitude	Longitude	Elevation (m)
UBC Totem	1108487	Vancouver	Point Gray	49°15’23.68”N	123°14’59.92”W	76
			decimal	49.26	-123.25	
			UTM coordinates (X,Y) (m)	481811	5456007	
Kitsilano	T2	Vancouver	2550 W 19th Ave	49°15’35.99”N	123°9’35.99”W	63
			decimal	49.26	-123.16	
			UTM coordinates (X,Y) (m)	488360	5456368	
YVR (upper-air)	T31	Richmond	3153 Templeton St	49°11’23.99”N	123°9’0”W	10
			decimal	49.19	-123.15	
			UTM zone10, coord. (X,Y) (m)	489070	5448585	
YLW	71203	Kelowna Airport		49° 58' 11.99"N	119° 17'59.99"W	454
			decimal	49.97	-119.30	
			UTM zone 11, coord. (X,Y) (m)	335073	5537827	

Ceiling height and cloud cover data were obtained from METAR[14] weather data from Vancouver International Airport (YVR). Vertical atmospheric data were obtained from twice-a-day sounding data at Kelowna Airport and surface meteorological data from the UBC Totem station. Kitsilano station data were analyzed for comparison purposes.

Terrain data were obtained from GeoBase database assessable through the CALPUFF View™ software (Lakes Environmental, 2012b). Canadian digital elevation data for region 92g were selected with coverage of 1:50,000 (Natural Resources Canada, 2012). In addition, the 1-Degree blocks DEM (Digital Elevation Model) data from WebGIS database for U.S. and Canada were

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[14] METAR weather data format is mostly used in aviation by pilots and standardized by ICAO (International Civil Aviation organization); available from: http://vortex.plymouth.edu/statlog-u.html. (Accessed January 3, 2018).

used for obtaining terrain elevations. Land use data (LULC) were obtained from Global Land Cover Characterization (GLCC) system for North America with 1 km mesh coverage.

Receptors, defined as anything of a value in the environment impacted by pollutants, were selected to be people at campus building locations. Over 500 entries containing: building ID, name, maximum occupancy, geographic coordinates, and heights were provided by the UBC Campus and Community Planning Department which were used to classify buildings into:

- Work-related, where residents, students, faculty, and staff reside during their work on campus. A total of 160 (out of 191 existing buildings) with classrooms, labs, administrative and academic offices were included as daytime (8 am to 7 pm) receptors, and
- Residences, classified as apartment buildings, high risers or townhouses were separated by individual dwellings resulting in 214 buildings. The occupants of those buildings were receptors during nighttime (8 pm to 7 am) but also during daytime as some residents would likely stay in those building.

A total of 374 campus buildings occupied by people at some point during days and/or nights were considered in this study. Buildings which are under development and/or for which data were not complete were excluded from this analysis. Building parameters for each selected building were entered in excel spreadsheet and used as discrete receptors in CALPUFF modeling and in iF calculations.

Another set of input data included source, i.e. stack parameters as presented in Table 3.2. Boiler stack filterable particle emissions were calculated as an average of 4 replicate emission tests conducted by a third party on July 17, 2012, following the procedures recommended by the BC Ministry of Environment (MoE, 2003).

Table 3.2 BRDF Source parameters.

Source ID	Description (Stack)	Height [m]	Diameter [m]	Exit T [K]	Exit velocity [m/s]	Emission rate [g/s]	Emission rate [kg/day]
						PM	PM
EN-02	Boiler with ESP Measured	20	0.76	477	8.43	0.028	2.419 Reported

Gas exit velocity was calculated as the ratio of the measured flow rate and stack cross-sectional area. The emission rate was calculated as a product of the measured flow rate and measured concentrations previously corrected to 8% O_2 as per permit. It was assumed that the emission rate was constant throughout the month selected for modeling, September 2012.

3.3.2.2. Model output data: ambient pollutant concentrations

CALPOST was set to produce output data as 1-hour and 24-hour average ground-level concentrations at each receptor expressed in micrograms per cubic meter (µg/m^3). Obtained data were imported from model output text files and organized in excel spreadsheets per modeling and iF assessment scenario (described in section 3.4) and for all considered receptors. All 1-hour data were then separated in daytime and nighttime periods. Mean, maximum, and minimum values were calculated for every daytime and every nighttime period. Summary results were organized in tables to enable comparison with AQO and to be added to background pollutant levels. In addition, mean values for each scenario and per receptor and daytime/nighttime period were imported in a separated spreadsheet to be used for iF calculations and overall campus pollutant levels and exposure scenarios. Results for September 2012 for $PM_{2.5}$ are summarized in Table 3.3 below.

Table 3.3 Ground-level $PM_{2.5}$ concentrations, UBC campus, September 2012.

Parameter	**All 374 receptors**	**Daytime 374 receptors**	**Nighttime 214 receptors**
Averaging period	24-hr $PM_{2.5}$[μg/m^3]	1-hr $PM_{2.5}$ [μg/m^3]	1-hr $PM_{2.5}$ [μg/m^3]
Mean	0.015 ± 0.031	0.019 ± 0.010	0.012 ± 0.020
Max	0.264	0.230	0.169
Min	0.002	0.001	0.002

Analyses of 1-hour $PM_{2.5}$ ambient concentrations across campus showed that nighttime mean concentration of $PM_{2.5}$ were 38% lower than daytime mean and 23% lower than 24-hour average. The maximum nighttime $PM_{2.5}$ 1-hour concentration (0.169μg/m^3) was only 27% lower than daytime maximum 1-hour $PM_{2.5}$ concentration (0.230μg/m^3) but 36% lower than maximum $PM_{2.5}$ concentrations for a 24-hour averaging period. Emission rate is relatively constant for current plant operating conditions. However, due to varying meteorological conditions (other parameters were kept constant), daily dispersion patterns varied.

3.3.3. Ambient air quality regulation and background pollutant levels

The Province of British Columbia adopted more stringent ambient (outdoor) air quality criteria for $PM_{2.5}$ in 2009 (BC MoE, 2016) due to their harmful potential to human health. A 24-hour objective is set at 25 μg/m^3 while annual objective is set at 8 μg/m^3 with planned target of 6 μg/m^3. Table 3.4 summarizes BC Air Quality Objectives (BC AQO) and Canadian Ambient Air Quality Standards (CAAQS) for particles and gases considered in this study as relevant to biomass emissions (BC MoE, 2016).

Table 3.4 Summary of provincial Air Quality Objectives (AQO) and Canadian Ambient Air Quality Standards (CAAQS) for selected contaminants.

Contaminant	Averaging Period	Criteria	Level	Air Quality Objective		Date Adopted
				μg/m[3]	ppb	
Carbon Monoxide (CO)	1hour	PCOs for Food processing, Agriculturally Orientated, and Other Misc. Industries	A	14,300	13,000	1975
			B	28,000	25,000	
			C	35,000	30,000	
	8 hour	PCOs for Food processing, Agriculturally Orientated, and Other Misc. Industries	A	5,500	5,000	1075
			B	11,000	10,000	
			C	14,300	13,000	
Nitrogen Dioxide (NO_2)	1 hour	Interim Provincial AQO	-	188	100 [a]	2014
		Provincial AQO	-	200		
	Annual	Interim Provincial AQO	-	60	32	2014
$PM_{2.5}$	24 hour	Provincial AQO	-	25 [b]	-	2009
		CAAQS	-	28 [c]	-	2013
	Annual	Provincial AQO	AAQO	8	-	2009
			Goal	6	-	2009
		CAAQS	-	10 [d]	-	2013

[a] Achievement based on annual 98th percentile of daily 1-hour maximum, over one year
[b] Achievement based on annual 98th percentile of daily average, over one year
[c] Achievement based on annual 98th percentile of daily average, averaged over three consecutive years
[d] Achievement based on annual average, averaged over three consecutive years

3.4 Population exposure and health risk assessment methodology

3.4.1 Dynamic intake fraction (iF)

Inhalation iF, representing a single-medium approach, is calculated as the portion which is being inhaled by exposed population (Nishioka et al., 2005; Jonathan I. Levy et al., 2002):

$$iF = \{ \sum_{i=1}^{m} \sum_{j=1}^{n} [P_{i,j} \text{ x } C_{i,j} \text{ x } BR_i]\} / Q_i \} \quad (3\text{-}3)$$

Where:

Q_i is the emission rate of a pollutant [kg/day] in a given time period i [hours] at a geographical area or location j; measured or calculated and as presented in the previous section,

$C_{i,j}$ is the ambient air pollutant concentration [mg/m^3] in time period i at receptor location j; these concentrations were obtained from CALPUFF modeling,

B_{ri} is the breathing rate [m^3/person/day] during time period i, and

$P_{i,j}$ is the number of people at a specific location and time.

3.4.1.1 Input values used for iF calculations

Emission rates were obtained by measurements performed at the active EN02 stack (Table 3.2) and ambient concentrations at each receptor were obtained from the CALPUFF modeling.

Breathing rate used in previous exposure-related studies was mostly averaged values and uniform for the population considered (as previously presented in Table 2.1). Some studies (Marshall et al., 2006) suggested 13 m^3/person/day for males and females combined (11.3 m^3/day for women, 15.2 m^3/day for men) based on age and activity. Most recent Exposure Factors Handbook (US EPA National Center for Environmental Assessment and Moya, 2011) suggested a breathing rate of 14.6 m^3/person/day which was estimated as the mean breathing rate for free-living normal-weight males and females combined, between 21 and 31 years old, which corresponded to the majority of UBC campus population. The same handbook suggested a long-term breathing rate of 15.7 m^3/person/day for the same category but based on the unweighted average of means from combined key studies. For short-term breathing rate, a person's activity was taken into consideration. For the "sleep or nap" activity, a mean breathing rate is 0.258 m^3/person/hour whereas for the "light-intensity" activity a mean breathing rate is 0.72 m^3/person/hour. In this study, improvements were made by separating daytime and nighttime breathing rates which led to more accurate estimates. For the daily breathing rate (dBR) in scenarios where only daytime was considered, 8.64 m^3/person/12 hr-daytime (0.72

m^3/person/hour x 12 hours) was used. Similarly, for the nightly breathing rate (nBR) in scenarios where only nighttime was considered, 3.096 m^3/person/12 hr-nighttime (0.258 m^3/person/hour x 12 hours) was used. In scenarios where daily iF was calculated over a 24-hr period, the breathing rate (BR) was 11.74 m^3/person/day as a sum of daytime and nighttime breathing rates (8.64 m^3/person/12 hr-daytime + 3.10 m^3/person/12 hr-nighttime).

The number of people at a specific location and time is another parameter directly related to iF which highly influences the intake fraction value. In general, a noticeable variation of population at university campus is due to a larger number of people working or attending classes during daytime versus a considerably lower number of people residing on campus during nighttime, which could have a significant impact on iF compared to a large city with relatively stable population density (Marshall et al., 2005a). Based on a widely varying criteria (Humbert et al., 2011), UBC, with population between 1500/nighttime and more than 4,000/daytime people/km^2, could be characterized as a densely populated urban area.

It was assumed that people would mostly be in work-related buildings and some in residences during daytime but only in residences (for those who live on campus) during nighttime. Time spent while commuting between buildings and exposure duration at locations along the routes were not included since it is considered to be negligible compared to the time spent at certain locations. Exposure potential was evaluated based on the exposure on ambient (outdoor) $PM_{2.5}$ concentrations, as indoor exposure is beyond the scope of this study. The estimated iF are thus expected to represent the upper limit of the actual values.

The number of exposed people is directly related to iF as expressed by equation 3-3. It was assumed that the exposure concentration is equal to the outdoor concentration in each of the two campus-related micro-environments, residential and daytime work-related buildings, while the exposure concentration is equal to zero while people are not on campus but rather in another micro-environment not affected or negligibly affected by the BRDF. Since the indoor fraction of ambient pollutant concentrations is generally lower than the outdoor concentrations (commonly used infiltration factor is 0.7 for $PM_{2.5}$) but will depend on the ventilation system and building age (Zhou and Levy, 2008), iF calculated as presented, is expected to be higher than the actual value or, in other words, iF from this study is a more conservative version.

All considered buildings were associated with corresponding number of people reported as the maximum building occupancy. Where maximum occupancy is given as a total number of residents in a housing complex, the number of people per building was disaggregated to be uniformly prorated, meaning that an equal number of residents is allocated to each building. As it was assumed that all people were in those buildings (attending classes, working, living) most of the time, occupancy of on-campus restaurants and museums was not considered to prevent double counting of campus population. Temporary workers or visitors to UBC campus were not taken into account as there is no record of such numbers and it is assumed that such number is negligible compared to regular campus inhabitants.

After assigning an appropriate number of people to each identified building, 16,406 persons were considered as the number of campus residents associated with 214 residential buildings occupied during nighttime. During daytime, estimated 49,256 people are distributed in 374 buildings out of which 160 are academic buildings with classrooms and labs and administrative offices (maximum occupancy minus 15% campus residents who are assumed to stay in residences during day) resulting in 46,795 persons and 214 are residential buildings which were assumed to be still 15% (2,461 persons) occupied during daytime. For a 24-hr averaging period, the number of persons on campus was calculated as an average of daytime maximum occupancy and nighttime maximum occupancy proportionally distributed in all 374 buildings (Table 3.5).

Table 3.5 UBC Campus population distribution as a function of diurnal dynamics.

Building/ Occupancy/period	**Residential buildings**	**Academic buildings and offices**
No of buildings	214	160
Max occupancy	16,406	49,256
Day-time occupancy	2,461(15% occupancy)	46,795
Night-time occupancy	16,406	0
Average 24-hr Occupancy	32,831 (8,203 in residences AND 24,628 in academic buildings)	

3.4.1.2 Scenarios and resulting iF values

To evaluate the impacts of space, time, population density and breathing rate variations on the estimated iF, five scenarios were considered:

Scenario 1: Base case – All averaged. No spatial, temporal or population dynamics was considered but only average values were used for all relevant parameters. This represents a typical box-model approach widely used in the past in dispersion modeling for health impact assessments. While performing dispersion modeling to obtain the ambient $PM_{2.5}$ concentrations, a nested receptor grid was set in a way to place receptors equally spaced at 50 m over the modeling domain of 2 km around the source. A total 4,859 receptors were included in modeling while 1,701 receptor sites were removed afterwards as they were over the ocean with no human exposure.

Obtained 24-hour average ground-level concentrations at each receptor were averaged over the entire campus area resulting in an overall average concentration of 0.01 $\mu g/m^3$. With 32,831 people being present on campus on average over 24 hours, iF was calculated to be 1.59 mg inhaled per kg emitted particles or 1.59 ppm (parts per million in mass).

Scenario 2: Spatial dynamics of receptors. In this scenario (Figure 3.4), spatial dynamics of receptors was introduced while other parameters remained as in scenario 1. All 374 buildings inhabited by campus population were entered in the model as discrete receptors and 32,831 persons were equally distributed to each building. Obtained average 24-hour ground level $PM_{2.5}$ concentrations for each receptor for the month of September 2012 were used to calculate iF for each receptor, with the results then plotted using ArcGIS software. The sum of iF for all receptors on the whole campus was found to be 2.28 ppm, based on values ranging from 0.0008 to 0.1115 ppm per receptor.

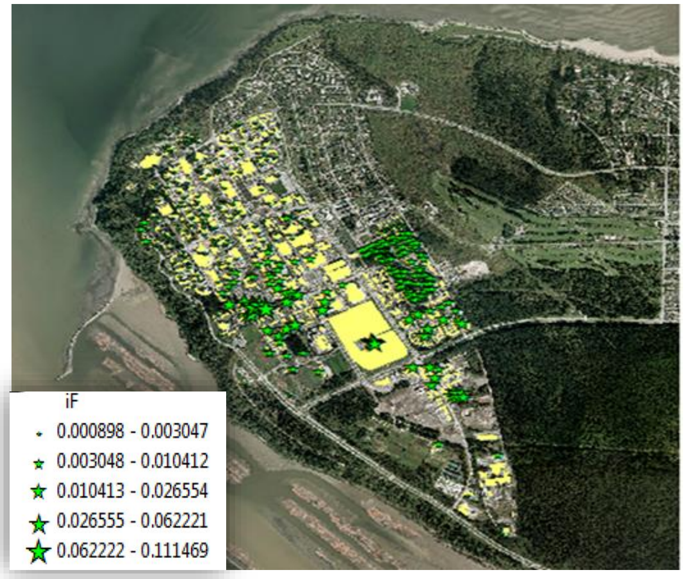


Figure 3.4 Scenario 2: iF for each building for September 2012.
Indicates buildings.

Scenario 3: Spatial and population dynamics. In addition to the spatial distribution of population in different buildings across the campus, this scenario (Figure 3.5), took into consideration population dynamics by assigning the actual number of people per building during the 24-hour period: 8,218 in residences and 24,628 in academic buildings, with 32,846 people in total. Model output, average 24-hour ground level $PM_{2.5}$ concentrations were then used to calculate iF for each receptor with different number of occupants per building according to building capacity. The sum of iF for all receptors, indicating iF for the whole campus, was 1.77 ppm, based on values ranging from 0 to 0.113 ppm per receptor.

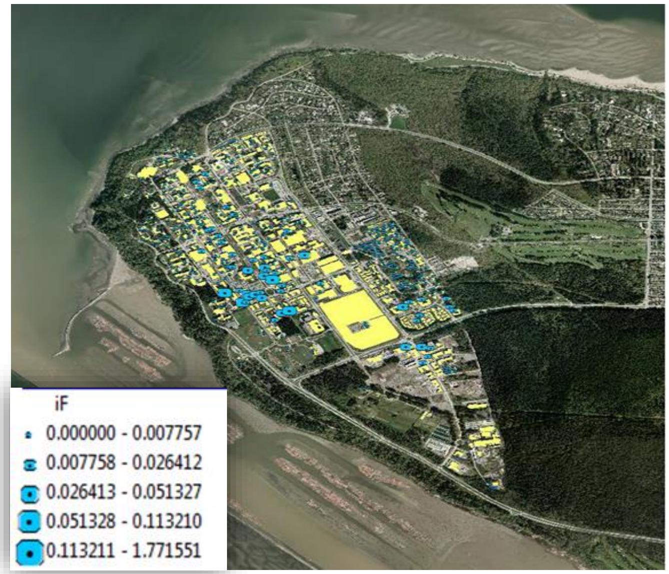


Figure 3.5 Scenario 3: iF for each building with actual occupancy, September 2012.

Comparison of scenarios 2 and 3 clearly indicated the importance of considering population dynamics and actual number of people at a certain location when calculating iF, resulting in a 22% lower iF than in scenario 2 but still 11.3% higher than iF obtained for a static model in scenario 1.

<u>Scenario 4: Spatial, population and temporal dynamics.</u> This scenario further introduces temporal dynamics to account for diurnal variations in meteorological parameters and significant diurnal campus population dynamics. This scenario considered separately daytime and nighttime periods when calculating iF. For the day-time period, a total of 374 buildings (160 work-related buildings, 214 residences) with 49,256 persons distributed as per each building's actual occupancy were entered in the model as discrete receptors. Similarly, a total of 214 residential buildings with 16,406 people representing actual occupancy per building were used in the model as discrete receptors for nighttime period calculations.

Model time averaging period was set to 1–hour, and 1–hour average $PM_{2.5}$ ground level concentrations at each receptor from the model output were used for iF calculations over the daytime hours and the nighttime hours, separately. Since daytime presented a 12-hour period, the breathing rate (which was not varying in this scenario) was accordingly adjusted to 5.87 m^3/person/12 hr by dividing daily breathing rate of 11.74 m^3/person/day by two. The same value for breathing rate of 5.87 m^3/person/12 hr was used for night-time calculations. The same period adjustment was done for emission calculations resulting in 1.21 kg of $PM_{2.5}$ /12 hours. iF was calculated for each receptor and summed up as per equation 3-3. for the daytime period resulting in iF being 2.19 ppm and the nighttime period when calculated iF was 1.18 ppm or almost half of daytime iF (Figure 3.6).

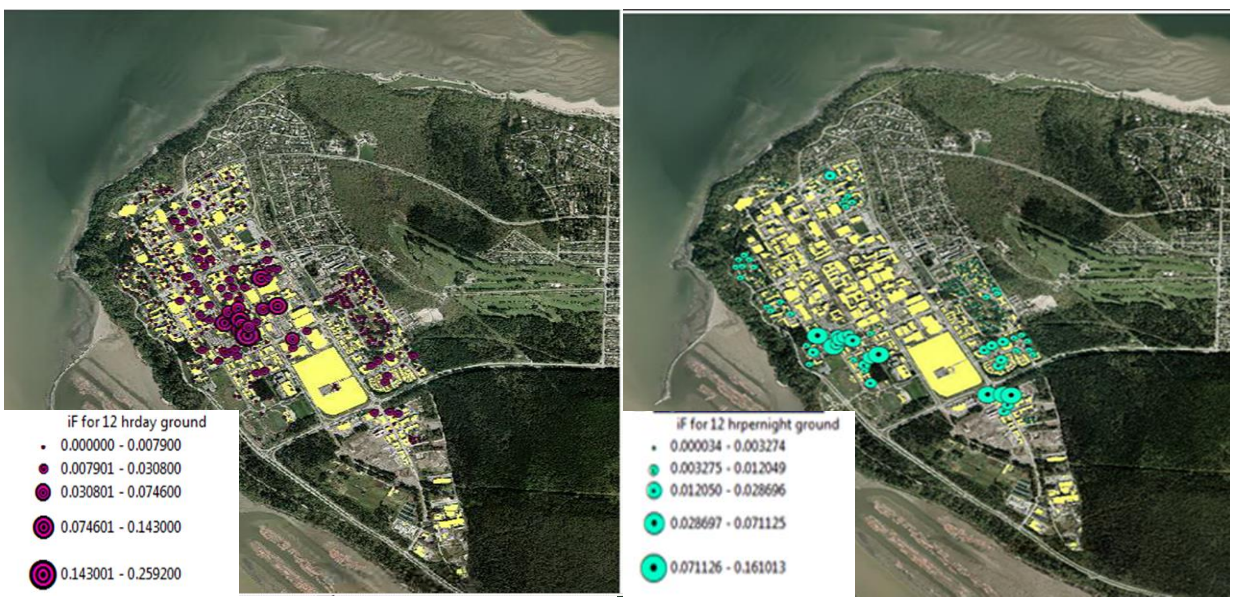
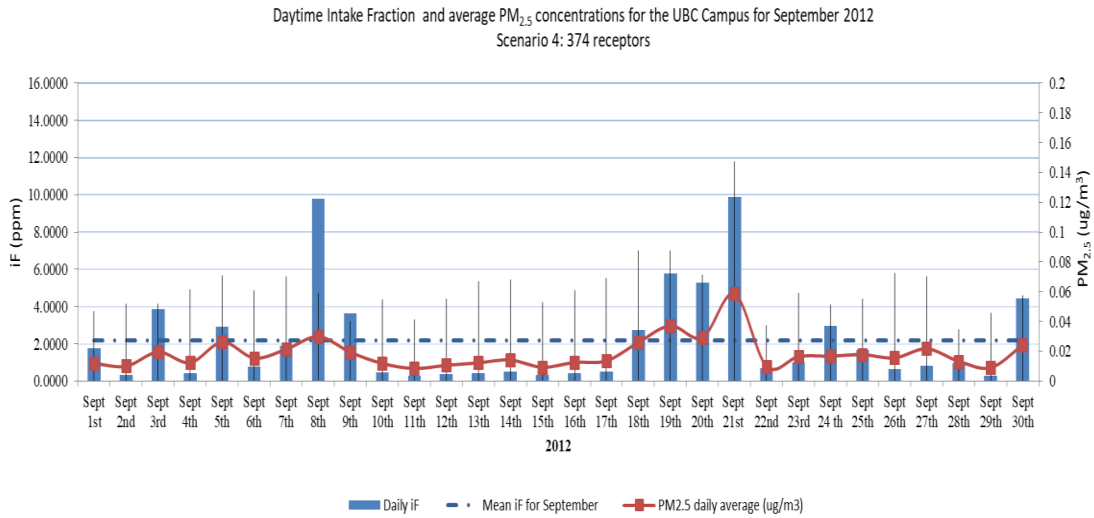


Figure 3.6 Scenario 4: a) daytime iF and b) nighttime iF for each building with actual occupancy for September 2012.

This scenario demonstrated the strong influence of day vs. night conditions. Taking an average of those two values gave a daily (24-hour) iF of 1.69 ppm which is only 6.2% higher than an average iF indicating some disadvantages of solely using averaging values where parameters such as diurnal population dynamics significantly vary over the averaging period. Daytime and nighttime variations of iF per date are presented in Figure 3.7.



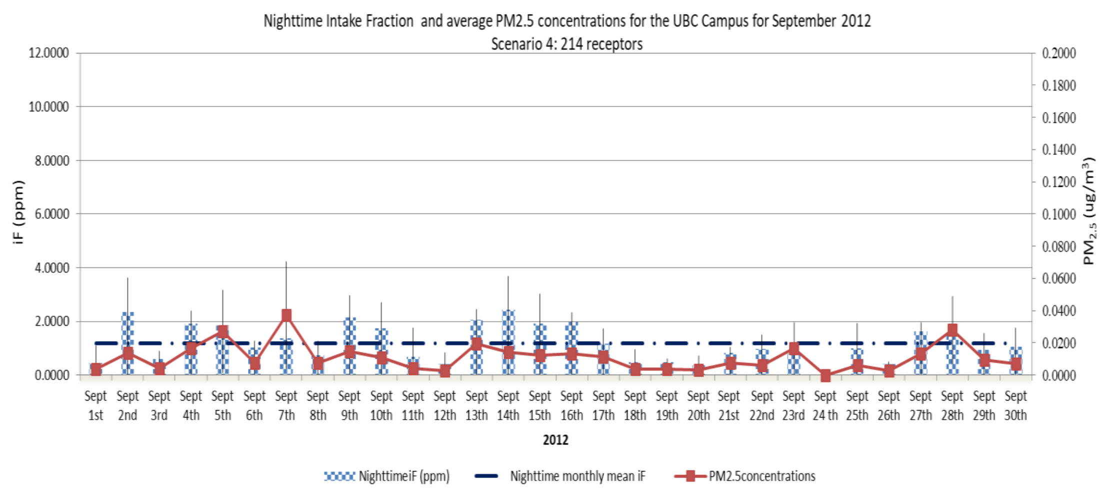
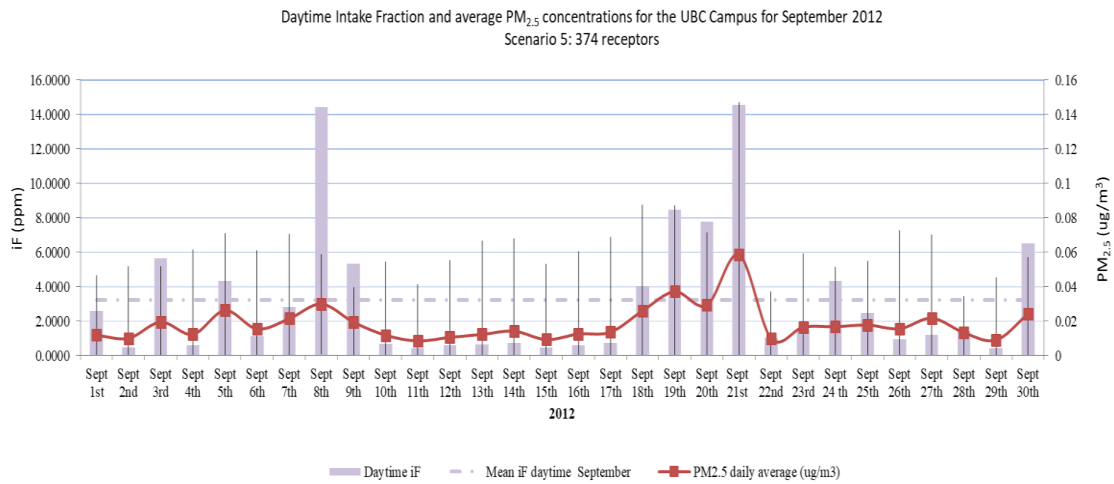


Figure 3.7 Scenario 4: daytime (upper graph) and nighttime (bottom graph) variations of iF for September 2012.

Scenario 5: Spatial, population and temporal dynamics, varying BR. In the final scenario, (Figure 3.8), breathing rates for day and night were used, with 8.64 m^3/person/12 hr for the daytime and 3.10 m^3/person/12 hr for the nighttime as previously explained. iF was calculated for each receptor, resulting in a total daytime $PM_{2.5}$ iF of 3.23 ppm and 81% lower iF for nighttime (0.62 ppm), a strong indication of the significance of diurnal variations in parameters used in iF calculations. Subsequently, iF for a 24-hour period, calculated as an average of daytime and nighttime iF, was 1.93 ppm or 21.4% higher than in scenario 1.



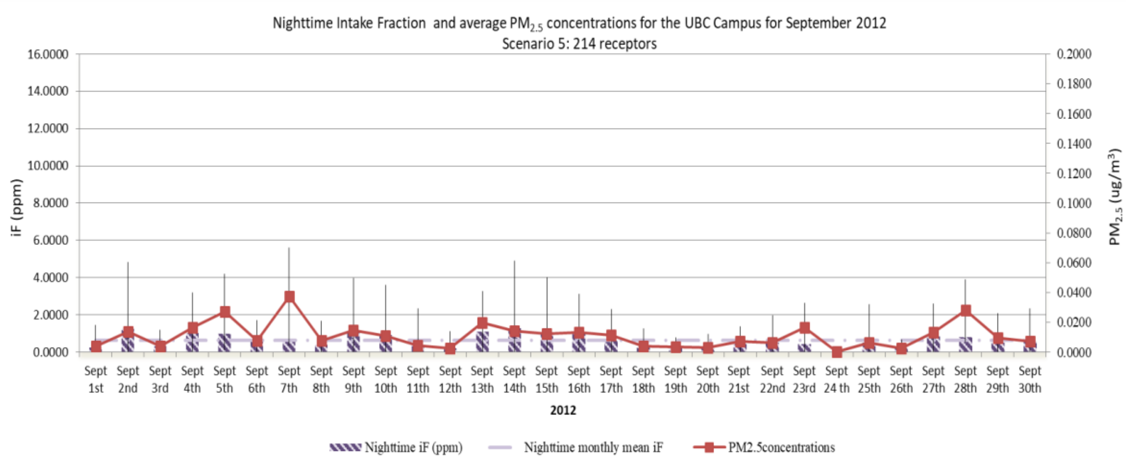


Figure 3.8. Scenario 5: UBC campus iF for September 2012 distinguishing day vs night periods with spatial and temporal dynamics, and varying BR.

Results from all five scenarios are presented in Table 3.6. The iF results from the five modeled scenarios tend to emphasize the importance of introducing high resolution spatial, temporal and population dynamics along with varying breathing rate in the assessment of local health impact for DES systems located in densely populated communities.

Although fine resolutions of a range of parameters have previously been recommended by some researchers (Xu et al., 2013; Dhondt et al., 2012; Marshall et al., 2006), none of the studies so far has evaluated variations in iF for biomass-based district energy systems in community settings such as university campuses with high spatial and temporal resolutions and population dynamics. It was demonstrated here that the introduction of spatial dynamics (scenario 2) by replacing a nested grid of receptors (which represented a uniform receptor distribution as space-averaged receptors), with actual discrete locations of receptors, resulted in an overall increase in iF by 43%. Introducing day vs night, i.e. temporal dynamics (scenario 4), provided more accurate estimates of pollutant concentrations at receptors as a result of different day and night air circulations and consequent pollutant dispersion.

Table 3.6 Modeling scenarios and calculated iF and IS.

SCENARIO Parameter	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
Spatial distribution receptors/buildings	NO Nested grid	YES 374 daily	YES 374 daily	YES 374 Daytime 214 Nighttime	YES 374 Daytime 214 Nighttime
Population dynamics	NO 32,831 people	NO 32,831 people (uniformly prorated/building)	YES 32,831 people (actual occupancy)	YES 49,256 Daytime 16,406 Nighttime (actual occupancy)	YES 49,256 Daytime 16,406 Nighttime (actual occupancy)
Temporal dynamics Day/Night	NO 24-hr	NO 24-hr	NO 24-hr	YES 12-hr Daytime 12-hr Nighttime	YES 12-hr Daytime 12-hr Nighttime
BR dynamics Day/Night	NO BR=**11.74** m^3/pers./day	NO BR=**11.74** m^3/pers./day	NO BR=**11.74** m^3/pers./day	NO BR=**5.87** m^3/pers./12-hr	YES **8.64**m^3/pers/daytime **3.10**m^3/pers/nighttime
$PM_{2.5}$ concentrations averaging period	24-hours	24-hours	24-hours	1-hour	1-hour
iF[mg/kg] =					
Σ $iF_{I,j}$daily=	**1.59**	**2.28**	**1.77**	**Av.=1.69**	**Av.=1.93**
Σ $iF_{I,j}$Daytime=	n/a	n/a	n/a	**2.19**	**3.23**
Σ $iF_{I,j}$Nighttime=	n/a	n/a	n/a	**1.18**	**0.62**
iF% change from scenario 1	0	+43.0%	+11.3%	+6.2%	+21.4%

Additional consideration of different breathing rates for daytime and nighttime (scenario 5), demonstrated significant diurnal variations in iF by up to 81%. More significant temporal variations are expected if the emission rate, which corresponds to the heat and power demands in full scale DES, also varies during day and night because of higher heating demand in the night during winter and higher hot water and electricity demand in the day during summer. Calculated iF could further be used to estimate human health impacts resulting from a particular source, as presented by Humbert et al. (2011) and outlined in the next section.

3.4.2 Health-related Impact Score (IS)

Two indicators, the dynamic intake fraction (iF) and human health-related impact score (IS) were used to evaluate the health impacts from emitted $PM_{2.5}$ and gaseous pollutants in this study. These metrics relate the environmental fate of pollutants to the exposure, dose–response, and severity of response (Michael Z. Hauschild., Ed. and Mark A.J. Huijbregts. Ed., 2015). IS was expressed in terms of disability-adjusted life years [DALY], obtained from equation 3-4: (Michael Z. Hauschild., Ed. and Mark A.J. Huijbregts. Ed., 2015)**:**

$$IS = m \cdot iF \cdot EF_{health} \tag{3-4}$$

Where:

m is the mass of emitted pollutant [g],

iF is the intake fraction per pollutant [ppm or 10^{-6}, µg inhaled/g emitted],

EF_{health} is a human toxicological effect factor [DALY/kg inhaled].

EF_{health} is 7.00E-04 DALY/kg $PM_{2.5}$ for particulate matter, 7.31E-07 DALY/kg for CO and 8.91E-05 DALY/kg for NO_2 (Quantis, 2012).

A human toxicological factor is obtained from the IMPACT2002+vQ2.22 database (Quantis, 2012), which includes the damage or adverse respiratory effects caused by inorganic substances ($PM_{2.5}$, biogenic and fossil CO and NO_2). The combination of iF and EF_{health} results in a characterization factor (CF) which expresses the increase in the number of DALY per unit mass of a pollutant emitted into the atmosphere. It should be noted that the EF_{health} values from IMPACT2002+ are based on observations relevant to the European countries, which may not represent the situations in North America very well. Therefore, interpretation should be rather focused on relative values among different scenarios. However, including site-specific iF and mass of emitted pollutants in the IS calculations increases accuracy in estimates.

3.5 Environmental footprint methodology

Carbon footprint and water footprint are the most common methodologies used to evaluate impacts in urban environments; however, other environmental compartments (such as air) also need attention. The Urban Metabolism (UM) is a widely used concept in urban environments for evaluating flows of energy and matter in and out of cities but does not assess environmental impacts (Mirabella and Allacker, 2017). Life Cycle Assessment (LCA) is a powerful tool for evaluating all-encompassing environmental footprints of products and activities over their entire life (Hiloidhari et al., 2017). Thus, for bioenergy applications, LCA is widely used to compare impacts of all life stages to fossil fuel utilization and to determine if reducing fossil fuels and substitution with bioenergy can benefit societies.

As presented in the literature review of 94 LCA-related studies by Cherubini and Strømman (2011), half of the reviewed studies directed the assessment towards the climate change impact category by calculating GHG and energy balances but did not consider other impact categories. A number of locally conducted studies outlined benefits and drawbacks of biomass utilization in Canadian context. For example, Pa and collaborators (2012) analyzed emission and energy flows for wood pellet produced in British Columbia and estimated environmental footprints of production, conversion and export of such pellets. The study found that 295 kg of CO_{2eq} is released for every tonne of pallets produced in BC and exported. If such locally produced pellets find their application in BC to replace firewood, human health impacts could be reduced by 61%, ecosystem quality impacts by 66% and climate change impacts could be reduced by 53%.

Life cycle assessment (LCA) can be performed following the recommendations of ISO 140044:2006 (ISO, 2006). Schematically, as presented as in Figure 3.9, the LCA framework consists of four stages which are described in detail below.

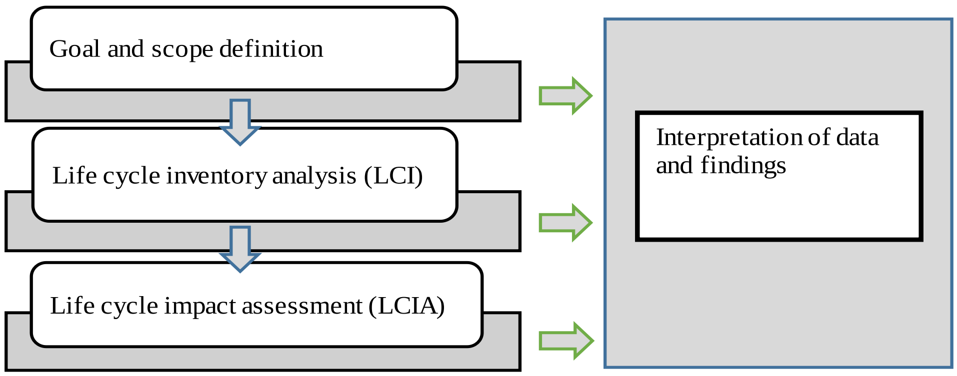


Figure 3.9 LCA framework.
Source: Based on ISO (2006).

3.5.1. Goal and scope definition

During this stage, since it inherently involves subjectivity, it is very important to carefully define the goal and scope of the study to minimize user's influence on results. The goal should: a) explicitly describe the application and intended audiences; for example, a study to be used only internally could be structured differently than the one publically available for which weighting step during the impact assessment phase is rather replaced with a peer review process; b) clearly describe the reasons for conducting the study, in other words, whether the study is just an informative one or it aims at providing a proof. The study can serve more than one purpose.

The scope of the study aims at describing methodological choices, assumptions, and limitations. The most important to clearly be defined are: a) Functional unit (FU) and reference flow – a comparison basis which is often a difficult task due to different performance of products and/or services which need to be compared; b) initial[15] system boundaries – since not all processes and products along the way need or have to be included so it is helpful to clarify what impacts the results; c) criteria for inclusion of inputs and outputs – which refers to the selection of a threshold below which an input or an output is not considered. ISO 14044 recommends using several criteria for such a threshold, for example, defining a percentage below which the mass inflow will not be accounted for; d) dealing with multifunctional processes – which happens when processes end up in more products; some of the ISO 14044 recommends are system expansion or allocation which is applied in attributional LCA analysis.

3.5.2. Life cycle inventory (LCI) analysis

This is the most demanding stage which includes data collection. Some secondary data are already available if a particular software like SimaPro is used or could be obtained from literature. Basically, two types of data need to be collected: a) background data - for the production of generic materials, transport, wastes and energy; b) foreground data – which refer to a specific product and/or a system that is being modeled. In both cases, data collection is a comprehensive process which encompasses: literature review, site visits, interviews, allocation considerations, data quality, confidentiality issues with data providers, etc.

3.5.3. Life cycle impact assessment (LCIA)

LCIA aims at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product or a process over their entire life, either from "cradle-to-

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[15] The term "initial" is often used as LCA is an iterative process.

grave" (from raw material extraction to waste disposal) or "cradle-to-gate"(from raw material extraction to the point of sales). ISO 14040/44 specifies that:

- Classification and characterization are mandatory elements of the analysis, while
- Normalization, ranking, grouping and weighting are optional elements.

Characterization is about assigning an impact category to the elementary flows from the inventory. This process considers the substances' ability to contribute to different environmental problems. For example, CO_2 will have impact on climate change while CFCs will have impact on climate change and stratospheric ozone depletion. However, although CO_2 and CFCs contribute to the same category, the magnitude of their impacts is different; in such case IPCC equivalency factors are applied (1 for CO_2, 4,660 for CFC-11, for a 100-year time horizon) (IPCC, 2013). Units of the results will be [kg CO_{2eq}]. Similarly, other substances are dealt with during the characterization stage by applying appropriate characterization factors.

The ISO standard allows the use of impact category indicators that are either "midpoint impacts" or "endpoint impacts". Generally speaking, indicators that are chosen close to the inventory results (midpoint) have a lower uncertainty but endpoint indicators are a favorable choice for decision makers. Impact categories used in practice are presented in Figure 3.10.

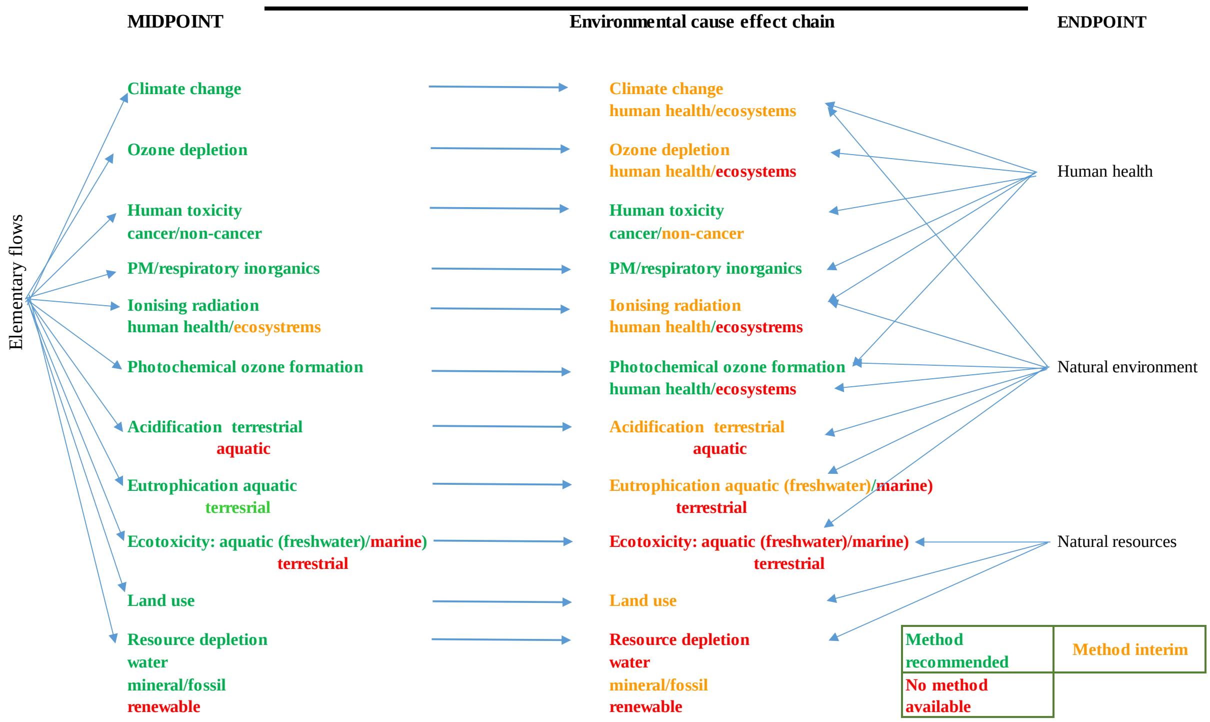

Figure 3.10 Scheme of the impact categories dealt with in ILCD Handbook on Life Cycle Impact Assessment at midpoint and at endpoint.
Source: Based on Sala et al. (2012).

A number of impact assessment methods, built on science-based environmental mechanism, have been developed over the years. One of the drawbacks of methods used with LCA methodology in general is that they are mostly developed for northern and middle Europe, the USA and Japan.

3.6 Conclusions

The novelty of this work lays in the improvement of an impact assessment approach for the biomass district energy systems, which accounts for all local-scale variations, from actual population density (as opposed to averaged census data commonly used in assessments), to local spatial and temporal micro-climatological and local spatial orographical conditions at the biomass plant site. It was shown that the proposed comprehensive methodology gave more accurate and realistic estimates of ambient concentrations at receptors stratified to follow the diurnal atmospheric processes which impact the pollutant dispersion, and consequently more accurate estimate of intake fraction accounting for dynamic variations of population and breathing rates.

When the dynamic variation of all parameters is accounted for (Scenario 5), the real dynamic nature of iF is captured. Neglecting microclimatic characteristics such as site-specific diurnal circulation patterns which influence pollutant dispersion or not considering short-term variation of parameters on a local scale such as population dynamics may lead to underestimation of iF by more than 20%. This amplifies the importance of incorporating both spatial and temporal dynamics in estimating the exposure (i.e. iF) in assessing the health impact of district heating systems in densely populated areas. These results confirm that this improved methodology could be generalized, i.e., applied to any source for which the impact assessment is sought in order to realistically evaluate the local impacts. The practical application of this methodology is presented in Chapter 4 for assessing local health impact and in Chapter 5 for assessment of global climate change impacts of biomass plants.

Chapter 4: Impact assessment of the UBC district heating system on local air quality and associated health risks [16]

4.1 Introduction

The main objective of this chapter is to fill the knowledge gap about local environmental (ambient air quality) and social (human health) impacts of newly and rapidly developing DES in community settings. Analysis presented in this chapter first applies an improved assessment method established and tested in Chapter 3 and then presents results obtained by evaluating local air quality and human health over five operational DES scenarios for a one-year period so to account for diurnal and seasonal variations of considered parameters. Operational scenarios were selected to feature the combined operation of BRDF and PH since BRDF commencement in June 2012 and then hypothetical, future scenarios in which the entire heating demand would be met by natural gas only or a scenario where the entire heating demand would be met by biomass (clean solid wood waste) only. Additional scenarios were introduced for sensitivity analysis to estimate the impacts of changing population dynamics and emission rates on output vales. Implications of such operational regimes on ambient air quality and subsequently on campus' population exposure are discussed.

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[16] A version of this chapter is published: **Petrov, O**., Bi, X., & Lau, A. (**2017**). Impact assessment of biomass-based district heating systems in densely populated communities. Part II: Would the replacement of fossil fuels improve ambient air quality and human health? Atmospheric Environment, 161, 191–199. https://doi.org/10.1016/j.atmosenv.2017.05.001.

4.2 District heating at UBC Point Gray campus

Energy for campus heating and hot water was generated exclusively by a PH boiler fired by natural gas (NG) at base load and supplemented by heating oil at peak load until June 2012 when a newly constructed biomass gasification plant BRDF became operational. The introduction of biomass was in line with the UBC's initiatives to reduce GHG by 33%, 67% and 100% by 2015, 2020 and 2050, respectively, from the 2007 level (UBC, 2015d). The plant was designed as a CHP although it has been mostly operated in the thermal mode since commissioned, using commercially proven Nexterra gasification technology.

4.2.1. Thermal energy demand and supply profile

The current plant operation in 2012/2013 was set as the base scenario. Hourly records of NG and fuel oil consumption as well as steam production were obtained for the 2009-2013 period. Daytime (8 am to 7 pm) and nighttime (8 pm to 7 am) data were separated for estimating diurnal fuel consumption and subsequently seasonal and annual fuel consumption. The June 2009 - May 2010 period was then chosen as a typical year of PH operation for meeting campus thermal energy demand, while June 2012 - May 2013 was chosen as a period which marked the first year of BRDF operation using biomass to produce heat for a portion of campus. For the PH, NG consumption was recorded in thousand-standard cubic feet [KSCF] and oil consumption in thousand-pounds [KLBS]. Steam production was also recorded in KLBS. All processed values were converted to SI units and were presented along with Imperial units in places as needed.

To calculate total energy input from different fuels, NG consumption was multiplied by its higher heating value (HHV) (Bossel, 2003), of 39.11 MJ/Nm^3 at normal/standard conditions

(1050 BTU/SCF), oil consumption was multiplied by its HHV of 46 MJ/kg, while steam produced (which represents energy output) was multiplied by HHV of 2.8 MJ/kg (1197 BTU/lb) at 1138 kPa (165 psig).

In 2009-2010, total energy input was 930 TJ, out of which 910 TJ was attributed to NG and 20 TJ to oil used only at peak load in winter season. A total of 884 TJ of steam was produced by the 3 boilers (mostly boiler # 5) in the PH with an annual average thermal efficiency of 95%. When the BRDF became operational, 823 TJ of steam produced was recorded as heat output by the PH boilers and 188 TJ as heat output from BRDF during the period of June 2012 - May 2013. Thus, almost 20% of total steam production was contributed by the BRDF. Fuel characteristics and consumption, and energy calculations are detailed in Appendix B.

4.2.2. Biomass supply requirements for fossil fuel replacement

BRDF utilizes locally collected and preprocessed solid wood residues with an average moisture content of 35% wet basis (or 54% dry basis) and a HHV of 19.3 MJ/kg of dry wood (Cot, 2016) to produce steam at 68% calculated average thermal efficiency, based on steam produced. On average 7,711 kg/hr (reported as 17,000 lb/hr) or 67,549 t/yr (148,920 KLBS/yr) of steam is produced at the BRDF at the current capacity, implying that on average 17,475 tonnes of wood waste are annually utilized by BRDF. Wood consumption was in this study attributed equally to all periods throughout the year.

Calculations showed that if gasification of wood waste were to replace the combustion of fossil fuels at PH in order to produce 823 TJ of energy as presented for 2012-2013 input energy of

1,210 TJ or 96,569 t of wood waste would be required. Adding the estimated wood waste consumption required for the BRDF during the same time period, a total 114,043 t of biomass residues would need to be gasified to meet the campus energy demand.

4.3 Scenarios for evaluating options for district heating at UBC

As presented in Table 4.1, five scenarios were considered, two of which served as sensitivity analysis.

Table 4.1 Summary of operational scenarios used in the DH impact assessment.

Operational scenario	Fuel used	Energy input [GJ]	Energy output [GJ]	Efficiency[%]
Scenario1: Base case- both BRDF and PH operational	Wood chips at BRDF, Natural gas for PH base load and fuel oil for peak load	276,560 904,637 13,694	188,061 822,965	68 89
Scenario 2: PH operational only	Natural gas	1,133,232	1,011,026	89
Scenario 3: BRDF operational only	Wood chips	1,486,803	1,011,026	68
Scenario 4: All BRDF with changed population dynamics	Wood chips	1,486,803	1,011,026	68
Scenario 5: PH operational scenario at 2009/10 level	Natural gas for PH base load and fuel oil for peak load	909,659 20,552	883,813	95

First four scenarios were based on energy input during the one year period June 2012 - May 2013:

Scenario 1 is the base case when both PH and BRDF were operational so energy demand was met by NG/oil and biomass;

Scenario 2 assumed the total energy input was provided by NG at PH only, whereas

Scenario 3 evaluated impacts in case of total replacement of fossil fuels with biomass and at BRDF in the future.

The other two scenarios were introduced to address uncertainty in data selection:

Scenario 4 is based on scenario 3 for biomass-related (BRDF) emissions but with varying population as a single most important parameter in calculating iF. Summer time population on campus was changed to reflect a more realistic scenario by assuming that 50% of people are on vacation and only 10% students stay in residences; consequently daytime population during summer was calculated to be 23,648 in 374 buildings while 1,604 persons stayed at nighttime in 214 buildings.

Scenario 5 is based on emissions from PH during 2009-2010, which corresponds to the operation before the BRDF facility was built in order to evaluate the impacts of different emissions (as a result of different energy demand) on ambient air quality and population exposure. As for PH operation, both natural gas and fuel oil were included for the base case scenario (Scenario 1) and for 2009-2010 (Scenario 5) as both periods were based on actual fuel usage data. Scenario 2, as a hypothetical case was based on the assumption that natural gas boilers will provide peak heating as planned for new District Energy Utility at UBC.

4.4 Emission characteristics and estimates

The pollutants to be considered in this part of the study are $PM_{2.5}$, CH_4, CO, CO_2, NO_x, N_2O and non-methane VOCs (NMVOCs). Since there are no prescribed ambient air quality objectives (AQO) for well-recognized GHGs (IPCC, 2015), VOCs, N_2O or CO_2 were not modeled in local health impact assessments. Available in-house data were analyzed along with previous studies; emissions of each pollutant were then either calculated or estimated using published pollutant emission factors (EF_p) and fuel consumption (Appendix B.2). BRDF and PH boilers' stack parameters were obtained from air quality permits and reports (Petrov et al., 2015). Estimated emissions are presented in Table 4.2 below.

Table 4.2 Estimated emission factors and annual emissions from biomass gasification (BRDF) and natural gas/oil combustion (PH).

Biomass at BRDF				**Natural gas and oil at PH**			
Pollutant	Estimated Wood waste gasification EF*	Estimated emissions 2012/13	Emissions total if all biomass 2012/13	Estimated NG-fired boiler EF**	Estimated oil-fired boiler EF**	Estimated emissions 2012/13	Estimated emissions if all NG/oil 2012/13
	EF_{wg}	E	E	EF_{NG}	EF_{OIL}	E	E
Units	[g/GJ]	[t]	[t]	[g/GJ]	[g/GJ]	[t]	[t]
$CO_{2\ fossil}$				49,170	68,478	45,419	55,721
$CO_{2\ biogenic}$	91,700	25,361	136.340				
CO_{fossil}				34.40	15.35	31.33	38.98
$CO_{biogenic}$	14.6	4.038	21.71				
$CH_{4\ fossil}$				0.9424	0.66	0.86	1.07
$CH_{4\ biogenic}$	9.03	2.497	13.43				
NO_x	73.10	20.217	108.69	40.95	30.71	37.46	46.40
N_2O	5.59	1.546	8.31	0.9015	0.80	0.826	1.022
$PM_{2.5}$	40	0.111	0.595	0.7785	6.14	0.788	0.882
NMVOC	4.3	1.189	6.393	2.2536	1.04	2.053	2.554

*Adopted from Pa et al (2011); wood waste includes forest harvesting residues and sawmill residues.
** Adopted from US EPA (1999, corrected 2010).

Emission factors for natural gas, fuel oil and wood waste (a mixture of forest residues and sawmill and planner mills residues), which relate the amount of emitted pollutants with an activity associated with the emissions (US EPA, 2009) are obtained from a recent study (Pa et al., 2011) and US EPA (US EPA, 2009; US EPA, 2003a; US EPA, 2003b). The estimated emissions were then calculated by equation 4-1 (US EPA, 2009):

$$E = A \cdot EF_p \cdot \left(1 - \frac{ER}{100}\right) \quad (4\text{-}1)$$

Where:

E is annual emissions [t/yr],

A is activity rate such as annual energy input [GJ/yr],

EF_p (used as EF_{NG} for natural gas combustion, EF_{OIL} for fuel oil combustion and EF_{Wg} for wood gasification) is uncontrolled emission factor [g/GJ_{input}] for pollutant p, and

ER is emission reduction efficiency [%] of the pollution control device. For instance, PM emission reduction efficiency is taken as 99% due to ESP at the BRDF (Pa et al., 2011), and 0% for NO_x or CO since no controls were installed for these pollutants.

Estimated annual emissions were therefore obtained by multiplying pollutants' respective EF_p by annual fuel input. Subsequently, monthly emission rates expressed in [g/sec] were calculated for each pollutant as a product of monthly energy production (separated for daytime and nighttime) and corresponding emission factor, and were used as inputs to the CALPUFF dispersion model in order to reflect the varying emission rates, thus generating more accurate estimated results of local air pollutant concentrations. For example, for the month of February 2010, emission rate for filterable $PM_{2.5}$ was estimated to be 0.029 g/sec for the PH which is slightly lower than the measured emission rate of 0.033 g/sec during a one-day event when boilers were operated at 45% max capacity. Similarly, for September 2012, the estimated $PM_{2.5}$ emission rate from BRDF is 0.0036 g/sec versus one-day measured emission rate of 0.0065g/sec, indicating that either the assumed ESP efficiency is higher than the actual ESP efficiency or there are variations of emissions throughout the month.

Detailed emission data calculated for daytime and nighttime for each month, used in modeling scenarios, are presented in Appendix C.

4.5 Local air quality assessment

A multilayer, non-steady-state puff dispersion model CALPUFF View™, version 7.2.0 (BC MoE, 2015; Lakes Environmental, 2012b), was used to compute the ambient concentrations of selected air pollutants at 374 discrete receptors (buildings with assumed maximum occupancy) on UBC campus within a campus area of 5 km x 3.5 km around BRDF, which was selected to be a reference point for modeling. The modeling domain extends 2.5 km in each of directions to the north, south and east from the plant and only 1km to the coast at the west (toward the ocean). Terrain, land use, and population data were used as presented in Chapter 3. Receptors' height was set equal to the breathing zone of 1.5 m. Ambient air pollutant concentrations were calculated as 1-hr averages [$\mu g/m^3$] and were imported into excel spreadsheet where daytime hours were separated from nighttime hours for diurnal pattern analyses. Meteorological data were extended to one year period June 2012 - May 2013. Three primary signature pollutants: $PM_{2.5}$, NO_x, and CO were modeled. Chemical transformations were not considered except for NOx, since NO was assumed to be completely converted to NO_2 (BC MoE, 2008). Background ambient concentrations for year 2012-2013 were obtained as an average over four air quality monitoring stations (Vancouver Kitsilano, North Delta, Richmond South, and Vancouver International Airport in Richmond) located in Metro Vancouver (Doerksen, 2014; Doerksen, 2013).

4.6 Health impact assessment

After ambient concentrations have been obtained, iF and IS were calculated as per methods presented in Chapter 3. A summary of calculated iF and IS for all 5 scenarios along with ambient concentrations (min, max and mean values) are presented in Appendix D. Incorporating dynamic iF in CF calculations brought about more accuracy to heath impact assessments than other methods such as those associated with commercial life cycle assessment software which uses static iF developed for average population density with an average daily breathing rates.

4.7 Discussion

Separating daytime and nighttime hours provides better insights in the effect of local wind circulation patterns, pollutant dispersion directions, and consequently human exposure. For example, an hour during daytime and one hour during nighttime were randomly selected to illustrate the diurnal wind pattern changes primarily caused by the sea- and land-breeze circulations (Petrov et al., 2015).

According, to Figures 4.1 (a, b, c), where nighttime wind fields at 10 m attitude indicate north and north-east wind direction causing land-breeze, ambient $PM_{2.5}$ concentrations on June 4, 2012 were a result of the plants' emissions dispersed across campus towards the southwest corner. The lowest maximum 1-hr concentration of 0.0068 $\mu g/m^3$ occurred in scenario 3 (Figure 4.1 a), when only BRDF (with installed ESP for particle control) was operational at full capacity compared to nighttime hours for other two scenarios. Besides, due to the locations of the two plants, the pollutant dispersion zone was broader when only PH is operational (scenario 2, Figure 4.1 b) or, when both PH and BRDF are operational (scenario 1, Figure 4.1 c). The more in-land location of the plant, the larger the impacted area of dispersed pollutants form such source.

Figure 4.1 (d, e, f) are pertinent to daytime hours that are characterized by ocean-to-land circulation, resulting in more dispersion of $PM_{2.5}$ towards the central part of the campus, southeast and east. It appears that the broadest area of particle dispersion characterizes scenario 1 with both plants being operational. Nevertheless, scenario 1 during this hour recorded 1-hr maximum ambient $PM_{2.5}$ of 0.189 $\mu g/m^3$, which was lower than the 1-hr maximum $PM_{2.5}$ of 0.351 $\mu g/m^3$ and 0.251 $\mu g/m^3$ for scenario 3 (biomass only) and scenario 2 (NG only), respectively.

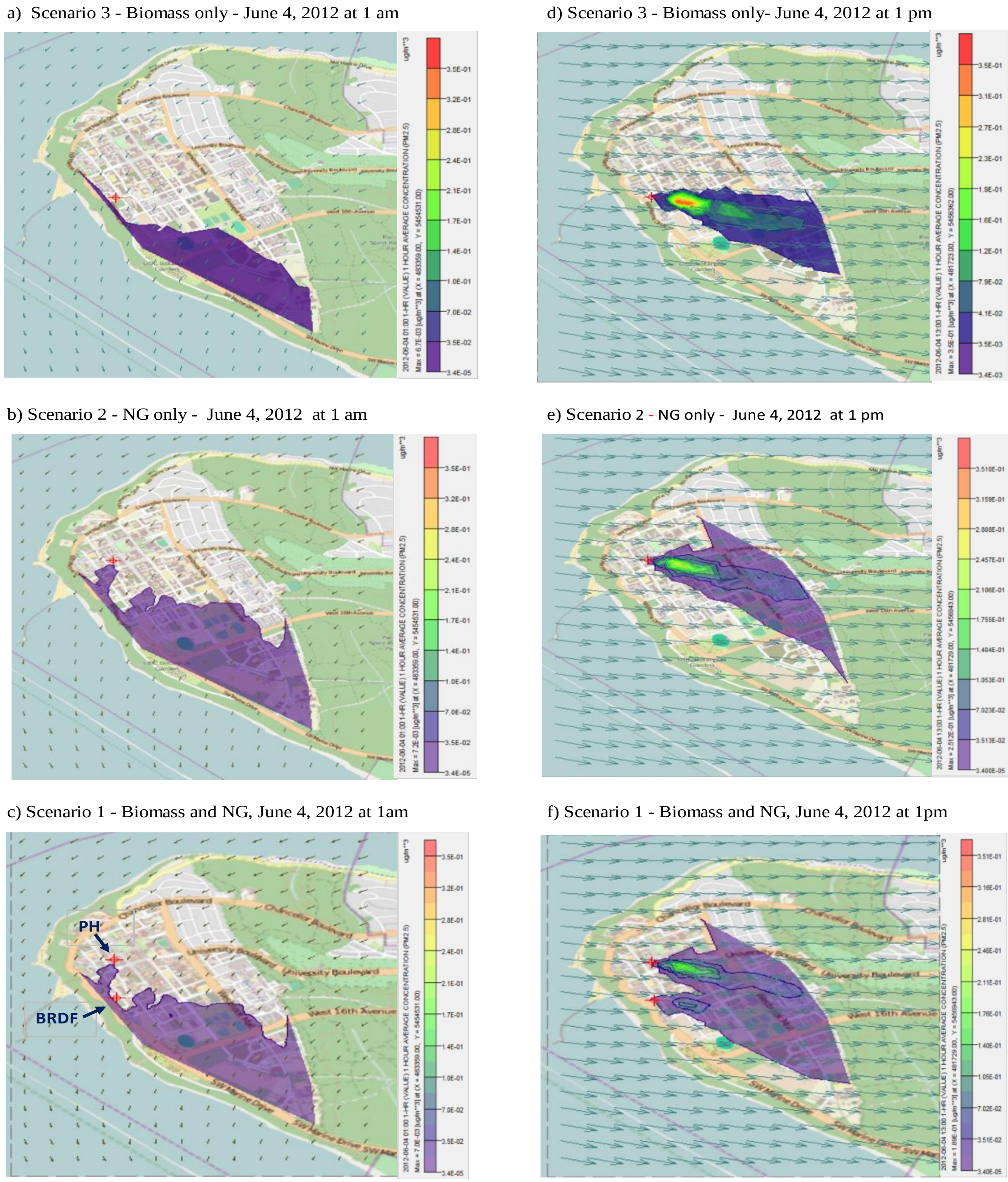


Figure 4.1 Wind circulation at 10 m altitude and projected $PM_{2.5}$ concentrations for June 4, 2012 at 1 am (nighttime) for Scenario 3 (a), Scenario 2 (b) and Scenario 1(c), and at 1 pm (daytime) for Scenario 3 (d), Scenario 2 (e) and Scenario 1(f). Arrows present wind fields obtained by CALMET.

The mean seasonal concentrations are based on 1-hr averages. These concentrations are higher during daytime for the four scenarios (2012-2013), which could be attributed to the expanded area of dispersion as previously explained rather than variation in the emissions (Figure 4.2).

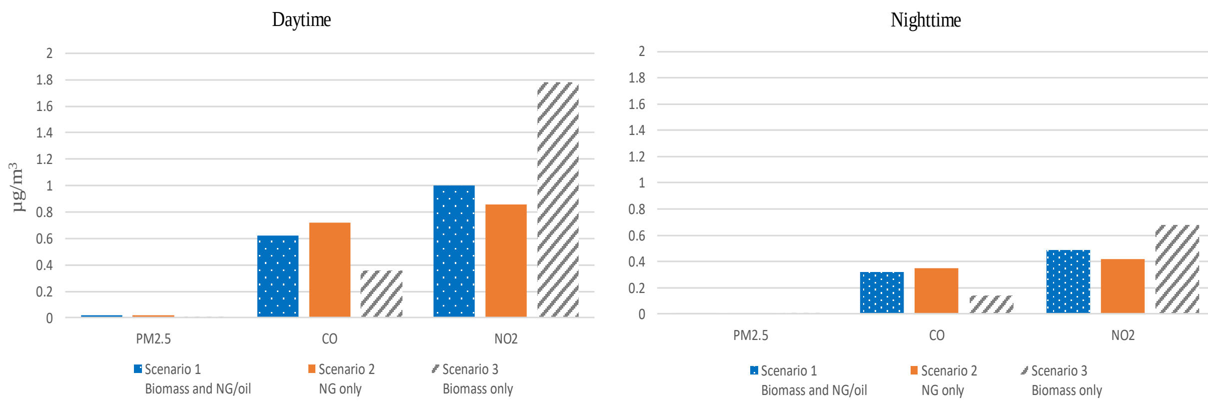


Figure 4.2 (a) Daytime and (b) nighttime average concentrations per pollutant and modeling scenario.

The mean ambient NO_2 concentrations resulting from natural gas combustion at PH are lower in scenario 5 (ranging from 0.311 µg/m^3 for fall nighttime to 0.961 µg/m^3 in spring, daytime) when compared with scenario 2 (0.369 µg/m^3 fall, nighttime to 1.048 µg/m^3 spring, daytime), as expected, because of the lower emissions in 2009/2010. The mean $PM_{2.5}$ concentrations associated with natural gas combustion are higher than those associated with biomass gasification, and higher in the spring (mean = 0.020 µg/m^3, max = 1.85 µg/m^3 from NG and mean = 0.012 µg/m^3, max = 1.14 µg/m^3 from biomass) and winter (mean = 0.019 µg/m^3, max= 2.13 µg/m^3 from NG; mean = 0.013 µg/m^{3,} but higher max of 2.39 µg/m^3 from biomass) than in other seasons. Scenario 3 (only BRDF using biomass operational) has the lowest mean concentrations for $PM_{2.5}$ (due to installed ESP for particulate control) as well as CO as compared to other scenarios. The overall incremental $PM_{2.5}$ contribution to local air quality is at least one order of magnitude lower (1-hr values multiplied by 0.4 to obtain 24-hr average values or multiplied by 0.08 to obtain annual average values) (EPA, 1992), than the BCAQO (BC MoE, 2016). However, when the highest calculated 24-hr average $PM_{2.5}$ concentration of 1.28 $\mu g/m^3$ (Scenario 1, winter, nighttime) is added to the averaged maximum background 24-hr concentration of 23.8 $\mu g/m^3$, the resulting value is slightly higher than the BCAQO of 25 $\mu g/m^3$. The location of this maximum is north of PH, and occurred on December 7, 2012 at 7 am when winds started shifting from north-east to south and south-east which indicates that PH emissions were likely a major contributor. Emissions from UBC can contribute to possible exceedance of the BCAQO if the Vancouver Kitsilano monitoring station measurements are excluded which will lead to higher averaged maximum background levels of 24.17 $\mu g/m^3$, suggesting that non-compliance with ambient air quality standard is possible in case of northern winds which would add particles emitted from PH to the already higher background maximum levels around YVR and south Richmond of 30 $\mu g/m^3$, as reported for 2013 (Doerksen, 2014).

Ambient concentrations of NO_2 are significantly higher for the biomass scenario than the NG scenario. While the mean NO_2 values are between 0.563 and 2.284 $\mu g/m^3$, there exist noticeable peak concentrations during daytime and nighttime for all seasons except summer for scenario 3. All of these 1-hr maximum hourly concentrations exceeded the 1-hr BCAQO of 200 $\mu g/m^3$ with the highest being 436.87 $\mu g/m^3$ on February 9, 2013 at 4 pm when southwest winds directed NO_2 to the location just northeast from BRDF (Civil and Mechanical Engineering building). The second highest maximum of 373.73 $\mu g/m^3$ occurred on November 5, 2012 at 4 pm with similar wind patterns affecting the Wayne and William White Engineering Design Centre, located northeast from BRDF. It should be noted that a most conservative approach of 100% conversion of NO to NO_2 was applied. This assumption should be verified by comparing the estimated values with measured ambient NO_x and NO_2 concentrations at surrounding air quality monitoring stations. Background averaged maximum 1-hr NO_2 ambient concentration was 94 $\mu g/m^3$.

Ambient CO concentrations for the scenarios where PH operation is dominant are up to three times higher than when emissions originate from BRDF. Yet the values are still low compared to the 1-hr BCAQO of 30,000 $\mu g/m^3$. Maximum concentration of 115.18 $\mu g/m^3$ (Scenario 2, fall, daytime) is 5% of the existing background value of 2,295 $\mu g/m^3$. The results for all 5 scenarios are summarized and provided in Appendix D.

With respect to health impacts (iF and IS) estimates, it is observed that NO_x gives rise to higher impact than $PM_{2.5}$ although the impact per unit mass NO_x (EF_{health}) was 10 times lower than $PM_{2.5}$, because the uncontrolled NO_x emission from biomass district heating system was much higher than controlled $PM_{2.5}$. It should be noted that NO_x has been well recognized as a major air pollutant emitted from biomass combustion systems without NO_x emission control device. iF for the UBC campus over the 2012-2013 period was low (70 ppm) for scenario 3 in the case of biomass totally replacing natural gas. It is even lower (59 ppm) for scenario 4 when the population decreases during summer time, which is a logical outcome since iF is proportional to the population. Scenarios 2 and 5 have almost the same iF of 104 and 107 ppm, respectively[17]

[17] This slight difference in values is likely due to rounding numbers throughout multiple calculation stages in order to obtain iF.

demonstrating that varying emissions from the same source (only PH is operational) during two different years do not affect iF, although intake amounts will be different. The base case scenario 1 is characterized by different iFs for each pollutant because pollutant emissions are additive from the two sources at different locations on campus.

The total health-related impact score (IS) is the highest for NO_2 ranging from 361 DALY (scenario 5) to 677 DALY (scenario 3). This is followed by $PM_{2.5}$ with IS ranging from 25 DALY (scenario 4) to 64 DALY (scenario 2) and 62 DALY (scenario 5). Impact score for CO ranges from 1 to 3 DALY across the scenarios. It appears that IS for NO_2 is highly influenced by high emissions of this pollutant especially from biomass gasification in scenario 3, which brings the overall IS for scenario 3 to 708 DALY, making the total replacement with biomass the least favorable option. It should be noted that a potential introduction of NO_x control device at a NO_x reduction around 70% (Babcock Power Environmental, 2008) could bring IS for NO_x down to 203 DALY and overall IS for biomass heating to 233 DALY. Similarly, if in scenario 1, NO_x biomass-related emissions[18] were reduced by 70%, the total emissions would be reduced from 57,521kg to 43,408 kg so IS for NO_2 would drop to 339 DALY and overall IS for scenario 1 to 402 DALY, making the total replacement with biomass the most favorable option. $PM_{2.5}$, impacts are more significant for the scenarios with dominant use of fossil fuels (NG/oil) for PH operation. Overall, considering IS by combining pollutant impacts for the first three main scenarios, the use of NG appears to have the smallest total health impact of 495 DALY (although the highest iF), followed by the distributed energy supply system (a split between PH and BRDF)

[18] In scenario 1, NO_2 emissions from BRDF are 20,161 kg and from PH 37,360 kg.

of 513 DALY whereas switching completely to biomass (with uncontrolled NO_x emissions) increases the human health burden by 28% (IS = 708 DALY, but the lowest iF) compared to the base case and 30% compared to PH as the sole operation.

4.8 Model performance evaluation

In spite of the high performance and sophistication of dispersion models nowadays used in practice, it is important that they are properly validated due to possible economic, environmental and public health implications of predicted results. Model validation can be scientific, statistical or operational. Scientific and operational validation of CALPUFF View™ has been safeguarded by US EPA (US EPA: SCRAM, 2015) and Lakes Environmental (Lakes Environmental, 2012b). Statistical validation is the most common and appropriate where model results are being compared against measured values. Such process addresses uncertainty associated with factors such as input values (Chang and Hanna, 2004). It should be noted that randomness of natural processes (such as atmospheric turbulence and dispersion) leads to inherent uncertainty and makes validation and verification of atmospheric models very difficult. Nevertheless, evaluation of model results via comparison with measured values gives better insight in upper and lower limits of possible values, i.e. pollutant concentrations. Evaluation can be performed as graphical (time series plots or scattered plots of modelled vs observed hourly concentrations) or statistical. Due to the scarce number of ambient air quality measurements on campus (only one monitoring station was installed for monitoring the impacts of BRDF emissions), graphical analysis is selected in this study.

Since BRDF became operational in 2012, instruments are set on the roof of an adjacent Marine Drive #5 residential building to monitor hourly concentrations of (NO_2) and fine particles ($PM_{2.5}$) which are selected for this analysis. Comparisons between ambient concentrations obtained as model output and continuous monitoring data of $PM_{2.5}$ were performed on an hourly basis.

4.8.1. Graphical analysis

Based on recommendations from US Environmental Protection Agency (US EPA, 2007), a period of interest (a day, a week, a season, etc.) of hourly values for $PM_{2.5}$ on July 17, 2012 was selected, as stack emissions were monitored on that day by a third party. Fine particle measured emission rate was 0.028 g/sec, flue gas exit temperature 477 K and gas exit velocity from the 20 m high EN02 boiler stack was 8.43 m/sec. Dispersion modeling was then performed using these measured emission data (assumed to be constant throughout the day) so ambient modeled $PM_{2.5}$ concentrations were checked against ambient monitoring data (Figure 4.3).

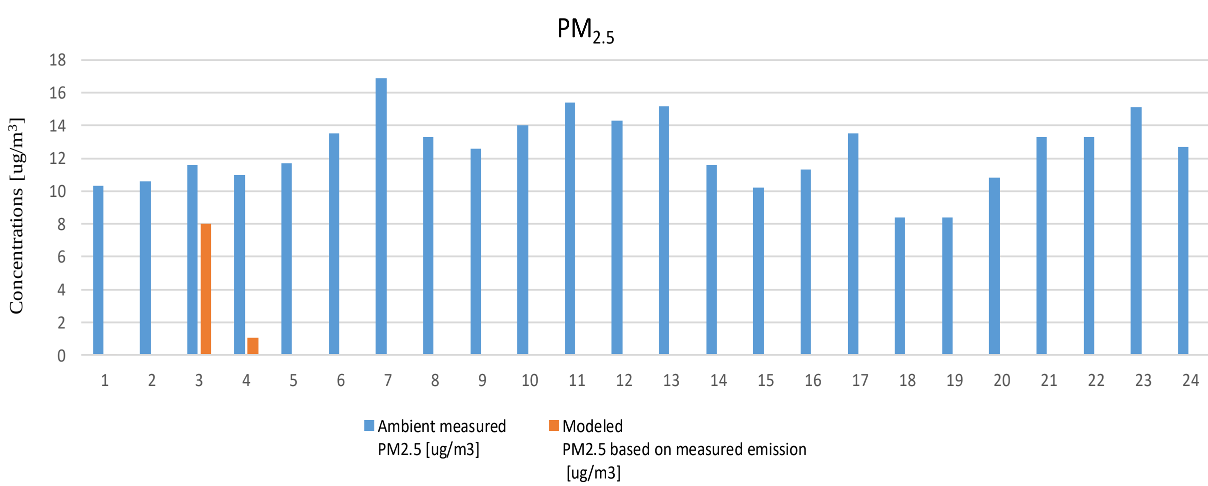


Figure 4.3 Graphical comparison of ambient measured and ambient modeled $PM_{2.5}$ concentrations for July 17, 2012.

The receptor was first set to be the top of the Marine Drive #5 residential building (45.38 m roof top height based on UBC data) where the ambient air quality monitoring instrument was installed and then at 25 m to check on concentrations in close vicinity of the stack. The horizontal ground distance between EN02 boiler stack and the Marine Drive building is estimated to be 80 m.

Modeled ambient concentration appeared to be noticeable only at 2 am and 3 am (values number 3 and 4 on the graph), and were lower than ambient monitoring data. In the recommendations of US EPA, performance evaluation priority may be given to those days with 24-hour average $PM_{2.5} > 65$ µg/m^3 (US EPA, 2007). However, this analysis was not performed, as measured $PM_{2.5}$ concentrations never reached that level during the period selected for analysis in this study (June 2012 to May 2013).

Data from the Totem campus weather station were considered to provide better understanding of local circulation patterns and consequently dispersion direction on hourly basis, with the results summarized in Table 4.3 below. In addition, MM5 wind fields[19] at10 m height (corresponding to anemometer height at the weather station) were also recorded as those data were used in modeling. It appears that calms were recorded at 2 am and 3 am with wind speed below 0.5 m/sec and wind directions for these hours being ENE and NNE, respectively as per Totem station. This could be interpreted as that any emissions from the stack at that time were likely lingering around the source, possibly in the vicinity of the nearby Marine Drive #5 residential

[19] MM5 data are based on a number of meteorological stations and satellite data which have been reanalyzed and gridded into a format suitable for input to the meteorological model. Calculations are also carried out for wind behaviour between grid cells (Source: Lakes Environmental).

building. At the same time, MM5 data indicated southern winds during these hours which could have dispersed pollutants towards Marine Drive building. Based on the wind directions recorded, any additional pollution reflected in a slightly higher measured concentrations of $PM_{2.5}$ than modelled would likely come from nearby sources located in the north-eastern quadrant[20] from the source.

Table 4.3 Measured and modeled $PM_{2.5}$ data and Totem station meteorological parameters for July 17, 2012.

Month	**Day**	**Hour**	**Ambient measured $PM_{2.5}$ [μg/m³]**	**Modeled $PM_{2.5}$ H=45.38m [μg/m³]**	**Modeled $PM_{2.5}$ H=25m [μg/m³]**	**Wind speed [m/s]**	**Wind direction Totem [deg]**	**Wind direction MM5**
7	17	0	10.3	0.0535	0.0363	1.6	91.7 (E)	S
7	17	100	10.6	0.0000	0.0000	0.62	60.2 (ENE)	S
7	17	200	11.6	7.9849	0.2612	0.27	72.7 (ENE)	S
7	17	300	11	1.0658	0.0304	0.58	35.4 (NE)	S
7	17	400	11.7	0.0000	0.0000	0.24	249.7 (WSW)	SSW
7	17	500	13.5	0.0000	0.0000	1.1	109.7 (ESE)	WNW
7	17	600	16.9	0.0000	0.0000	1.2	79.4 (E)	WNW
7	17	700	13.3	0.0000	0.0000	0.98	100.1 (E)	WNW
7	17	800	12.6	0.0000	0.0000	1	248.4 (WSW)	WNW
7	17	900	14	0.0000	0.0000	0.4	157 (SSE)	WNW
7	17	1000	15.4	0.0000	0.0000	1	243.8 (WSW)	WNW
7	17	1100	14.3	0.0000	0.0000	1.83	277.1 (W)	WNW
7	17	1200	15.2	0.0000	0.0000	1.72	237.1 (WSW)	WNW
7	17	1300	11.6	0.0000	0.0000	1.52	242.9 (WSW)	W
7	17	1400	10.2	0.0000	0.0000	1.52	243 (WSW)	WSW
7	17	1500	11.3	0.0000	0.0000	1.48	203 (SSW)	SW
7	17	1600	13.5	0.0000	0.0000	1.5	164.7 (SSE)	SW
7	17	1700	8.4	0.0000	0.0000	1.37	170.3 (S)	SSW
7	17	1800	8.4	0.0000	0.0000	1.15	155.6 (SSE)	SSW
7	17	1900	10.8	0.0000	0.0000	1.07	153.2 (SSE)	SSW
7	17	2000	13.3	0.0000	0.0000	0.69	137.6 (SE)	N
7	17	2100	13.3	0.0000	0.0000	1.53	103.7 (ESE)	NW
7	17	2200	15.1	0.0000	0.0000	1.85	112.3 (ESE)	SW
7	17	2300	12.7	0.0000	0.0000	3.07	96.3 (E)	WNW

[20] North-eastern quadrant refers to locations from 0 degrees to 90 degrees, meaning north to east.

Likewise, for hours when wind was not blowing towards the receptor (Marine Drive #5 residential building), the expectation is that the modeled values will show zero concentrations, ie. there were no emission impacts from the source on particular receptor.

CALPUFF was used in many 'near-field' applications (distance from a source < 10 km). The better performance is demonstrated for predicting mean annual concentrations than short-term ones (Holnicki et al., 2016), and for larger distances (Rood, 2014). Inspite the possible issues with underestimating concentrations compared to Gaussian plume models (U.S. EPA, 2008), its use is justified in cases of complex wind fields (sea-land breeze), calms, lack of measured meteorological data (only one meteorological near-by station at UBC) as it can fully treat variation of meteorology in space and time unlike steady-state Gaussian models. Although some experiments confirmed that some other Gaussian models (such as ADMS[21] developed in UK) can better perform in the built environments than CALPUFF and SCREEN (Tominaga and Stathopoulos, 2016), other studies (Hajra et al., 2010) showed that such models cannot treat complex plume behavior due to turbulence caused by buildings as obstacles to the flow and as such may cause considerable errors in estimates of effects such as short-term exposure and unsteady processes. Vieira de Melo et al. (2012) concluded based on wind tunnel experiments that AERMOD will predict higher near-field concentrations than CALPUFF; the latter can also under-predict concentrations by a factor of two or more, depending on conditions. Another study (Cui et al., 2011) showed that CALPUFF can simulate flow in near-by complex terrain but can underestimate peak concentrations. A larger number of measured outdoor (ambient)

[21] ADMS - Atmospheric Dispersion Modelling System.

concentrations would be ideal to evaluate model performance using numerical methods such as in Holnicki et al. (2016).

When meteorological data were used for interpretation of results for a longer period of time such as for the whole month of July 2012, the following was observed:

- When the wind was blowing over 393 hours from 45 deg. to 125 deg. i.e., from NE, E to SE, the average wind speed was 1.6 m/s and maximum measured $PM_{2.5}$ concentration was 23.1 µg/m^3 while maximum modeled concentrations were 7.98 µg/m^3 based on measured emission rates. Wind direction and speed indicate contributions from sources located to the NE, E and SE from the source.
- When the wind was blowing over 157 hours from 135 deg. to 225 deg. i.e., from SE to SW, meaning that the plume from the BRDF stack should be carried towards the building, with the average wind speed of 1.4 m/s, measured maximum $PM_{2.5}$ concentration was 25.7 µg/m^3 while maximum modeled concentrations were 2.08 µg/m^3. There is an assumption that building (sources) located SE from BRDF and vehicular traffic to the S and SW of BRDF contribute to higher measured concentrations than modelled.
- When the wind was blowing over 166 hours from 226 deg. to 315 deg. i.e., from SW, W and NW, the average wind speed was 1.5 m/s and measured maximum $PM_{2.5}$ concentration was 26.7 µg/m^3, the highest of all measured over this period. Modeled maximum concentrations were 0.039 µg/m^3. This indicates a low likelihood of contributions from the BRDF stack but increased particulate levels could be rather originating from the vehicular traffic in Marine Drive.

4.9 Conclusions

Based on the results of this study, it appears that the health impact from a biomass-based energy system installed with an efficient PM control device mainly results from the uncontrolled NO_x emission, followed by PM and CO emissions, among all criteria air pollutants. The lowest iF for this option indicates the importance of the plant location relative to community setting where the smallest number of people would be affected by plant emissions since iF is mostly influenced by the number of people exposed. On the other hand, it appears that a distributed district heating system with combined NG and biomass may have an advantage over a community-based centralized heating system in terms of overall health impact. This option can have smaller iF, depending on plant locations compared to the location of a single plant (like in case of PH) and also lower overall health impacts compared to a single biomass energy supply system. Further research is needed to confirm the initial findings presented in this study that multiple emission sources and combined use of NG and biomass could lower health impact compared to community-based centralized biomass plant.

It is worth of noting that considering locally obtained dynamic iF for calculating CF may also bring more accuracy in assessing local impact in life cycle assessment studies instead of using the CFs based on consensus data and other population density data averaged over a large area, e.g. the European continent. The “emission factor method” was used to estimate emissions in this study. Future research on impact assessment should focus on conducting direct measurements of the emissions in order to support scale-up and draw conclusions on the basis of seasonal and annual variations. It would be useful that a community installs ambient air monitoring stations on several “hot spots” for obtaining real-time concentration data. This would be especially important for monitoring pollutant concentrations during periods of possible increased concentrations (since concentrations obtained by CALPUFF could be underestimated) which can violate air quality objectives.

Depending on the capital and operating costs (including the cost for emission control) as well as energy efficiency being acceptable on a local scale, either splitting emissions into more than one source at different locations and different fuel types or a single source at the least-impact-based location with biomass as a fuel and emission control could be a viable option. In the decision making process about community-based energy systems, associated costs for different options should be balanced with lowering ambient air pollutant concentrations and hence reducing the risk of exceeding the BCAQO, as well as reducing population exposure.

Chapter 5: Global impacts of the UBC district heating system

5.1 Introduction

The presence of greenhouse gasses (GHG) in the atmosphere is responsible for the global warming impact and consequently affects the Earth's climate. Evaluation of GHGs is regularly performed and reported on the national and provincial levels in Canada. The Ministry of Environment and Climate Change Strategy BC reported a 2.7% increase in GHG emissions from 2011 to 2014 but a 9% decrease from 2004. Although population in the province is steadily growing, GHG intensity (GHG emissions per person) is in decline during the last decade with a small peak in 2013 as shown in Figure 5.1. The same figure illustrates the steady decline in GHG intensity when measured with respect to GDP (BC Ministry of Environment and Climate Change Strategy, 2016).

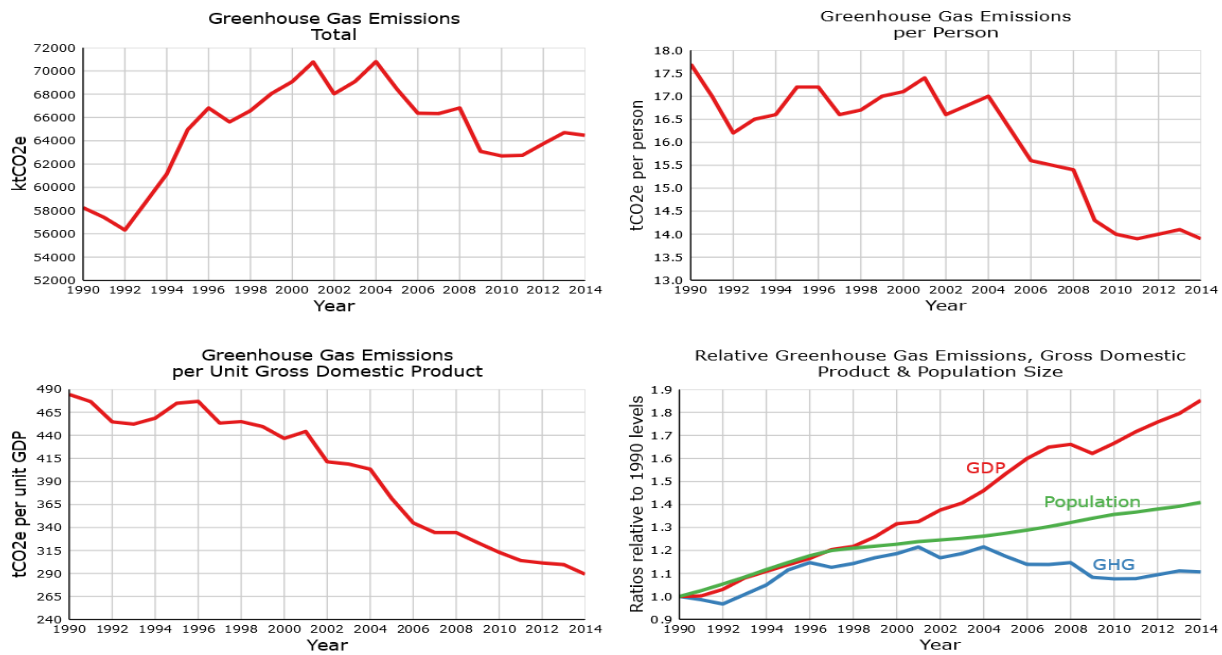


Figure 5.1 Trends in GHG emissions in BC 1990 – 2014.
Source: BC Ministry of Environment and Climate Change Strategy (2016).

The largest amounts of GHG in the province come from the energy sector where transportation and stationary combustion sources, namely space heating, were identified as the major sources of GHG emissions (BC Ministry of Environment and Climate Change Strategy, 2016). Thus, it is of a paramount importance to evaluate GHG emissions from existing and new energy sources.

Assessment of environmental impacts on large spatial and temporal scales, such as global scale, requires different methodologies from those used for assessments on a local scale. Life Cycle Assessment (LCA) is an effective tool commonly used for those purposes, which is widely used to evaluate the impacts of different fuels over the entire life cycle. Many studies used this method to evaluate impacts of bioenergy systems but high variability of results among studies points towards a need for harmonization in assumptions and the selection of a functional unit, system boundaries, allocation methods, carbon cycle modeling etc. (Muench and Guenther, 2013).

5.2 Quantifying global impacts of UBC district heating

To estimate the energy use and the emissions and impacts associated with the supply and use of biomass and fossil fuels (natural gas and oil) for district heating, two assessment approaches are used, one of which is an attributional life cycle assessment (LCA) methodology following the recommendations of ISO 140044:2006 (ISO, 2006), as explained in Chapter 3.

5.2.1. Feedstock sourcing and characterization at the UBC Point Grey campus

Wood feedstock for the BRDF is supplied by a recycling company Cloverdale Fuels Ltd. (Cloverdale) located in Langley, BC. A number of visits to Cloverdale served as the first step to collect data on source industries, their locations and quantities of woody biomass collected, processed and stored at the Cloverdale's site in Langley, BC. Data were organized in a spreadsheet and distances traveled from each site to Cloverdale and from Cloverdale to BRDF were calculated. The company receives woody biomass from many different places and produces wood fuels for many different customers, but only the wood residue retrieved and sent to BRDF was studied here.

Once received at UBC, a variety of biomass properties are regularly measured. Wood bulk density is determined following the CEN/TS 15103 method (CEN (European Committee for Standardization), 2005a). Moisture content of received wood-fuel samples was measured following the CEN/TS 14774 method (CEN (European Committee for Standardization), 2005b). Moisture content can be expressed on wet basis as:

$$MC_W = (W_{wet} - W_{dry})/W_{wet} \cdot 100) \quad (5\text{-}1)$$

where MC_W is the moisture content on wet basis [%], W_{wet} is the mass of the sample before drying [g] and W_{dry} is the mass of the sample after drying [g].

Conversion to moisture content on dry basis (MC_d, %) is performed using the following equation:

$$MC_d = MC_w/(100 - MC_w) \cdot 100 \quad (5\text{-}2)$$

The high heating value (HHV) of the sample was then measured and recorded following CEN/TS 14918 method (CEN European Committee for Standardization), 2005) using a bomb calorimeter (Model 6300, Parr Instrument Company).

5.2.2. Goal and Scope

The primary goal of this analysis is to quantify the global warming impact as it is an important global impact for energy systems (IEA Bioenergy, 2011). For the reference of energy system, the UBC campus energy production scheme was used over the period of June 2012 – May 2013 and it was evaluated against the two other energy system schemes: 1) if all energy demand for campus heating was met entirely by biomass; and 2) if all energy demand was met entirely by fossil fuels. Global warming impact results from LCA were then used together with the local health impact to discuss the possible trade-offs between local and global impacts for the selection of district heating systems. The functional unit was selected to be MJ of energy (for each fuel) produced to enable comparison among scenarios. The amount of heat produced in the period June 2012 – May 2013 which is equal to 1,011 TJ, is marked as the annual energy output which is equal for all considered scenarios.

System boundaries for unit processes and transportation segments for LCA are presented in Figure 5.2. Since biomass feedstock supplied to UBC is waste material, upstream processes associated with plantation, harvesting and processing of trees to generate biomass residues were excluded. Fossil fuel-related processes include extraction and refining, transmission and combustion at UBC Power House. Global warming impacts were evaluated using two commercially available software packages: GHGenius, version 4.03 ($(S\&T)^2$ Consultants, 2013) and SimaPro, version 8.2.0.0 (PRé, 2016).

Foreground processes related to biomass for which site-specific data were collected include waste wood transportation from industrial sites to Cloverdale site and from Cloverdale to UBC, processing at the Cloverdale site, i.e. estimating energy and materials input and emissions output due to the use of wood transportation, machinery fuels, and gasification of wood residues at BRDF (Figure 5.2 a). As wood was treated as a waste material, emissions associated with upstream from tree plantation to wood waste generation were excluded from the system boundary in the current study.

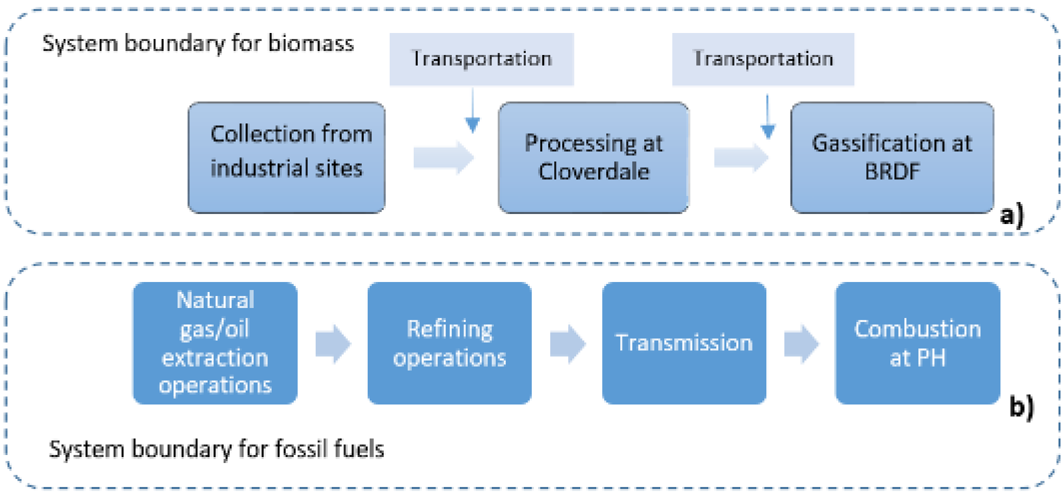


Figure 5.2 Process stages and transportation segments considered in evaluating global impacts of a) biomass and b) fossil fuels.

For natural gas (base load) and oil #2 (peak load) combustion, background data included upstream processes: extraction, refining and transmission whereas site-specific data were collected for combustion of natural gas and oil at UBC (Figure 5.2 b).

5.2.3. Life cycle inventory

Site-specific data, referring to actual Cloverdale and BRDF operations, were collected during the Cloverdale site visits through company's records and direct laboratory analysis of received wood feedstock. Emissions from BRDF wood gasification and natural gas/oil combustion at Power House (PH) were estimated based on published emission factors for natural gas (EF_{NG})

and oil (EF_{OIL}) combustion, wood gasification (EF_{wg}), and calculated actual fuel consumption for year 2012-2013 as presented in Chapter 4.

Data for natural gas and oil upstream processes from fossil fuel extraction to transmission to PH as well as transportation data (fuel-energy used and emissions factors expressed as [g/t-km]) were obtained from GHGenius v. 4.03 and entered in excel spreadsheet to calculate actual emissions (impact assessment approach 1) and entered in SimaPro v.8.2.0.0 for impact assessment (impact assessment approach 2). The types of energy consumption, both primary and secondary, considered in this study are: electricity, natural gas, fuel oil, diesel (middle distillate), and wood waste. Electricity supply mix in BC changed over the years shifting to increased use of natural gas and non-hydro renewables (Natural Resources Canada (NRC), 2015; Government of Canada, 2014; NEB, 2013), and 2013 was used as the base year in this study. The largest contribution to BC energy mix came from hydro (91.82%), natural gas and combustion of other fuels contributed with 1.62% and 1.68% respectively, steam from waste heat 0.15%, renewables (wind, tidal and solar) 0.28% and other generation 4.4%.

BC electricity generation intensity is presented in Table 5.1. The mass of methane per kWh electricity produced decreased since 1990s but CO_2 intensity increased compared to 2001 and 2012 whereas N_2O intensity varied over the years being higher in 2013 than in 2012 but lower compared to 2005-2010 period.

Table 5.1 Greenhouse gas intensity [g GHG/kWh electricity generated] in BC.

Year	1990	2000	2005	2010	2011	2012	2013	2014
CO_2 intensity [gCO_2/kWh]	17	35	24	23	13	11.1	14.9	14.3
CH_4 intensity [gCH_4/kWh]	0.004	0.009	0.007	0.007	0.004	0.003	0.003	0.003
N_2O intensity [gN_2O/kWh]	0.0006	0.001	0.0015	0.0015	0.0011	0.0007	0.0009	0.0009
Generation Intensity [gCO_{2eq}/kWh]	**17**	**35**	**25**	**24**	**14**	**11.4**	**15.2**	**14.7**

Source: (Environment Canada, 2017).

Biomass collection. Cloverdale collects waste wood from a number of locations, all situated in the Lower Mainland. The analysis of Cloverdale's client records, which were predominantly manufacturing companies dealing with import-export of wood products, identified 114 locations in radius of 100 km from the company (Cot, 2016).

Biomass transportation. Transportation considered delivering wood waste to the Cloverdale site and delivering processed wood waste to UBC by heavy duty vehicles (HDV), trucks which use diesel (middle distillate). GHGenius was used for transportation segment calculations. Input data included truck characteristics, namely, load and fuel consumption. The average trucks' fuel consumption in liters per distance traveled (L/100km) was calculated as:

$$Avg.Cons\ \left(\frac{L}{100\ km}\right) = \frac{Avg.Cons\ /week\ (L)}{Avg.Travel/week(travel)*Avg.Distance\left(\frac{km}{travel}\right)} * 100 \qquad (5\text{-}3)$$

This could also be calculated through energy consumption intensity expressed by kJ/tonne.km-shipped indicating the biomass load:

$$\text{Avg. Cons}\ \left(\frac{\text{kJ}}{\text{tonne.km}-\text{shipped}}\right) = \frac{\text{Avg.Cons}\left(\frac{\text{L}}{\text{km}}\right)*\text{Avg.km}\left(\frac{\text{km}}{\text{travel}}\right)*\text{E}_{\text{diesel}}\left(\frac{\text{kJ}}{\text{L}}\right)}{\text{Load}\ \langle\text{tonne}\rangle*\text{Avg.km}\langle\frac{\text{km}}{\text{travel}}\rangle} \qquad (5\text{-}4)$$

A total of eight trucks with 30 m^3 carrying capacity transport wood waste from designated sites to Cloverdale's site daily. For an average wood residue density of 187.4 kg/m^3 fully loaded trucks can transport 5.7 t of wood for each trip. The assumption of fully loaded trucks for each trip and an average of 3 trips per day was applied in calculations. Based on equation 5-3 and equation 5-4 the average truck diesel fuel consumption was 52.4 L/100 km. This consumption appeared to be higher than the average HDV consumption in Canada for 2013 of 40 L/100km ((S&T)^2 Consultants, 2013). Older trucks and urban area routes could be some of the reasons for the higher fuel consumption rates.

Biomass processing. Once delivered to the Cloverdale site, three different types of machinery, a diesel excavator, a diesel loader and an electrical grinder, were used to process wood waste. An excavator feeds a grinder yielding in wood chips smaller than 3 inches as required by UBC. A loader brings wood chips to the sheds to be stored before being loaded on trucks and transported to UBC. The energy consumption of each machine was expressed per tonne of wood. Cloverdale provided data for the average energy consumption of the loader and the excavator as well as the average wood chips production per day so that the consumption was calculated as:

$$\text{Avg. Cons}\left(\frac{\text{L}}{\text{t}}\right) = \frac{\text{Avg.Cons}_{\text{per day}}\ (\text{L/day})}{\text{Avg.tonne}_{\text{produced per day}}\ (\text{t/day})} \tag{5-5}$$

The data for the electrical grinder were not directly available from Cloverdale. Instead, the grinder energy consumption was calculated from the Cloverdale's electricity bills and daily grinder productivity. Cloverdale operations are 7 days per week, but the processing units are running only 5 days a week or on average 21 days per month. The final consumption per tonne of wood was calculated to be 51.3 kWh/t of wood waste (Cot, 2016).

GHGenius was used for estimating emissions from transportation and machinery fuels, since it uses the North America specific database. Output data from GHGenius included upstream emissions for each considered gaseous and particulate pollutant (here considered CO_2, CO, CH_4, N_2O, NOx as NO_2, SOx, NMVOC, PM). GHGenius also does not report biogenic emissions separately. Instead, biogenic EF were taken from another study (Pa, 2010) for subsequent impact analysis. Electricity mix and fuel characteristics for British Columbia in the year 2013 were used. Data of indirect emissions linked to the use of electric power are already included in GHGenius. Input and calculated data for the segment of collecting, processing (at Cloverdale) and transporting biomass from sites to Cloverdale and from Cloverdale to UBC as previously explained are presented in Table 5.2. Storage of wood waste and associated emissions were not considered.

Table 5.2 Transportation and wood processing data

Input Parameter	**Value**	**Units**	**Output/Calculated**	**Value**	**Units**
			Transport		
HDV Truck transport data	Distances & frequency travelled	3 trips/day	Average distance for 1 trip Industry to Cloverdale	27.2	km
		3 trips/day	Average distance for 1trip Cloverdale to UBC	51.6	
Truck capacity	40	Cubic Yards	Truck capacity	30.4	m^3
Number of trucks/trips to UBC	2-4[22]	3 trucks average	Total capacity for 3 trucks	91.2	m^3
Mass of wood received	91.2 x 187.4	m^3 x kg/m^3	Average mass of wood received/day	17.1	t
			Mass of wood received/truck	5.7	t
HDV fuel (diesel) consumption	0.5	L/km	HDV fuel (diesel) consumption	52.4	L/100km
HHV diesel	45.6 39	MJ/kg [23] MJ/L [24]	Fuel efficiency	2.271	MJ/t-km-shipped
Wood processing at the Cloverdale site (biomass production)			5 days/week = 21days/month		
Electricity for grinder per day	4,104	kWh	Consumption/ t (@80t/day)	51.3	kWh/t
Loader production/day	80	t	Loader consum./t (diesel)	1.25	L/t
Excavator production/day	80	t	Excavator consum./t (diesel)	1.25	L/t

[22] (UBC, 2015a).
[23] Source: http://hydrogen.pnl.gov/hydrogen-data/lower-and-higher-heating-values-hydrogen-and-other-fuels (Accessed October 4, 2016).
[24] Source: http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx (Accessed October 4, 2016).

Biomass and fossil fuel conversion. Once at the UBC site, the BRDF, wood chips are unloaded from the trucks and placed in one of the two bins **(**Figure 5.3 a). The second step is sorting wood chips with desired size for gasification (Figure 5.3 b) so that oversized wood chips could be separated and placed in a wood waste bin (Figure 5.3 c) and returned to Cloverdale.

Figure 5.3 Wood chips at BRDF: a) storage bin b) sizing c) oversized for oversized wood chips.

Wood characteristics, determined in the UBC lab are presented in Table 5.3.

Table 5.3 Wood chips characteristics.

Parameter	**Value and units**
MC_d	54**%**
HHV	19.3 MJ/kg (dry wood)
Average wood density	187.4 kg/m^3

UBC-owned natural gas distribution system[25] enables regular supply of natural gas from Shell Energy North America via FortisBC pipelines. Gasification of wood chips is carried out in BRDF and combustion of natural gas and oil in the PH. Emissions data for both plants (BRDF

[25] Source: http://energy.ubc.ca/ubcs-utility-infrastructure/natural-gas/ (Accessed April 10, 2017).

and PH) were calculated as presented in Chapter 4. Upstream (production of energy) and downstream (usage of energy) emission factors and emissions generated and obtained via GHGenius and UBC reports, are presented in Appendix E1 and Appendix E2, respectively. Emission factors for transportation stages are expressed in kg of pollutant emitted per tkm (traveling 1 km with the load of 1 t), [kg/tkm] while for processes emission factors are expressed in kg of pollutant emitted per MJ of energy input [kg/MJ]. Emissions are obtained by multiplying energy consumption and a corresponding emission factor for each pollutant.

5.3 Global impact assessment of UBC district heating options and discussion

5.3.1. Impact assessment approach 1

A spreadsheet model in MS Excel was used to calculate emissions based on upstream and downstream emission factors (EF) for different fuels used for both PH and BRDF which are presented in Appendix E1, Table E1-1 to E1-4. Based on the fuels consumption emissions were calculated for process and transportation stages using equation 4-1 and other parameters. For example, the annual emission of each pollutant resulting from the operation of a loader at the Cloverdale site is calculated as a product of fuel consumption (1.25 L per tonne of wood processed), mass of wood processed (t/day), 21 working days per month, 12 months per year (252 days) and HHV of diesel (39 MJ/L) which resulted in a factor characteristic for a particular scenario depending on the mass of wood processed. This factor is used as a multiplier for each respective pollutant EF [kg/MJ] upstream and downstream, as presented in Table E1-3. It should be noted that fuel efficiency was included and considered in GHGenius. The same approach was taken to calculate emissions of excavator and grinder as well as transportation stages (from industry to Cloverdale and from Cloverdale to UBC) for waste wood utilization. Natural gas and fuel oil combustion as well as waste wood gasification emissions were calculated in a similar way although presented upstream and combustion EF in Appendix E1 were multiplied by energy input calculated in Chapter 4. The analysis of emissions per processing and transportation stage was done for each scenario and it is expressed as annual GHG emissions in kg of CO_{2eq}.

Scenario 1 included the base case when both biomass at BRDF and natural gas and fuel oil at PH were used to meet the campus energy demand of 1,011 TJ in the period of 2012-2013. As depicted in Figure 5.4 the major contributor to annual GHG emissions (76.9 %) is natural gas combustion with 4.48E+07 $kgCO_{2eq}$ followed by upstream natural gas processing with 1.17E+07 $kgCO_{2eq}$ (20.1%). Oil combustion is responsible for 1.6% of total GHG emissions with 9.42E+05 $kgCO_{2eq}$ while wood gasification contributes only 0.8% with 4.88E+05 $kgCO_{2eq}$ of total emissions since CO_2 emissions are attributed mostly to biogenic CO_2. Other biomass-related processes contributed with less than 1% share of total emissions: wood processing at Cloverdale (1.12E+04 $kgCO_{2eq}$), and total wood transport (1.41E+05 $kgCO_{2eq}$). GHG emissions from upstream processing for fuel oil are negligible, 0.4% contribution to total GHG emissions (2.11E+05). It is clear that fossil fuel, namely natural gas usage, produces the largest amount of GHG. In addition, gasification/combustion of biomass does not account for net CO_2 emissions because they are regarded as neutral over life cycle, so the regulatory practices require reporting of $CO_{2biogenic}$ separately (BC Ministry of Environment and Climate Change Strategy, 2016).

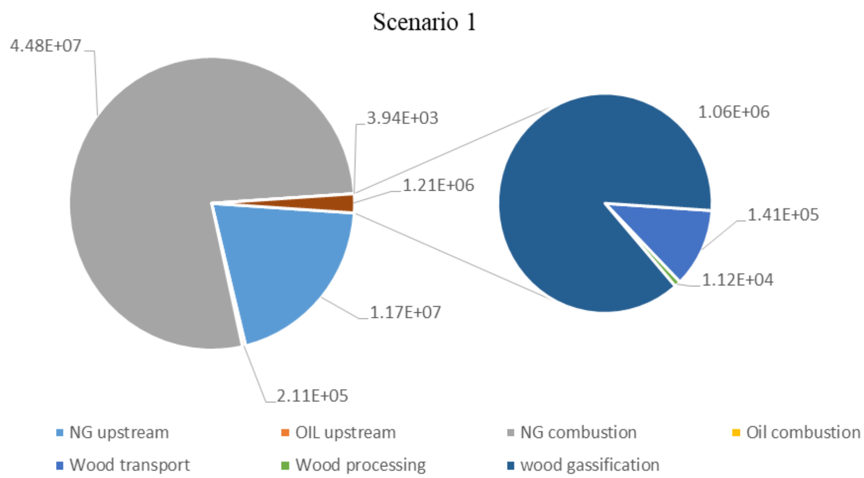


Figure 5.4 Scenario 1: Annual GHG emissions [kgCO_{2eq}] per life cycle stage for natural gas, fuel oil and biomass.

When contribution of pollutants from each stage is considered (Figure 5.5), major greenhouse gas, CO_2 fossil, originated almost completely from NG combustion followed by natural gas upstream processing, oil combustion, wood transport and wood processing. While N_2O and NO_x emissions could be attributed to biomass gasification and NG combustion, SO_x emissions of 1.61E+04 kg/year originated from oil combustion and upstream natural gas processing. Wood gasification N_2O emissions (1.55E+03 kg/year) are an order of magnitude higher than emissions from natural gas combustion (8.16E+02 kg/year). Particles which are of primary concern for health impacts are mostly emitted from natural gas combustion (7.04E+02 kg/yr) and wood gasification with ESP in place (1.10E+02 kg/year) followed by oil combustion (84.1kg/year) and wood processing (46.9 kg/year). A summary of numerical vales are presented in Table E2-1.

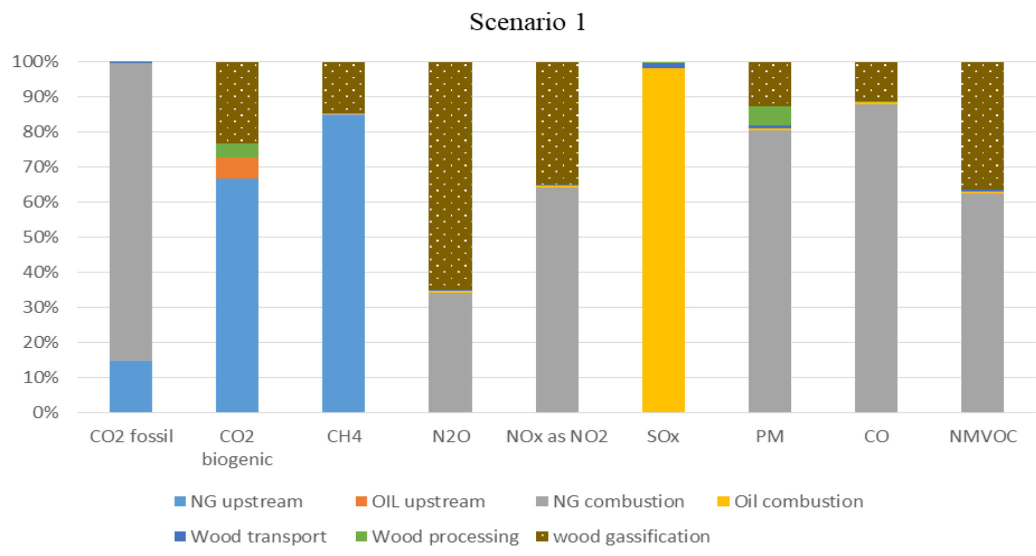


Figure 5.5 Scenario1: Pollutant emission contributions from different life cycle stage

Scenario 2, which considers a district heating option with natural gas meeting the campus' energy demand, includes emissions from upstream processing and the combustion process (Figure 5.6). It is obvious that upstream processing with 1.47E+07 kgCO_{2eq}/year contributes to GHG emissions less than combustion with 5.61E+07 kgCO_{2eq}/year.

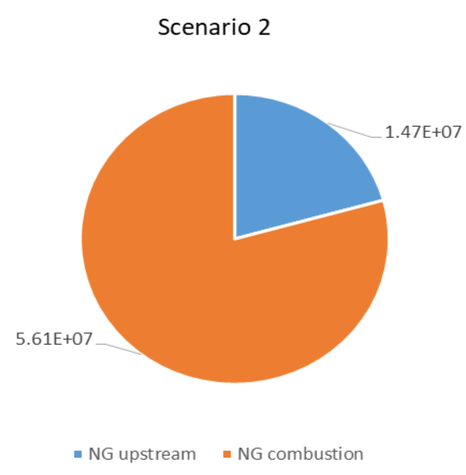


Figure 5.6 Scenario 2: Annual GHG emissions [kgCO_{2eq}] per life cycle stage for natural gas.

The analysis of stage-wise emissions per pollutant (Figure 5.7) indicted that the major contributor to CO_2 (5.57E+07 kg/year), N_2O (1.02E+03 kg/year) and CO (3.90E+04 kg/year) emissions is natural gas combustion whereas upstream processes are mostly associated with emissions of CH_4 (1.81E+05 kg/year), NO_x (5.16E+04 kg/year), SO_x (1.17E+04 kg/year) and NMVOCs (3.92E+03 kg/year). Emissions of particulate matters are associated with both process stages, 6.75E+02 kg/year from upstream processes and 8.82E+02 kg/year from natural gas combustion. Numerical values are presented in Table E2-2.

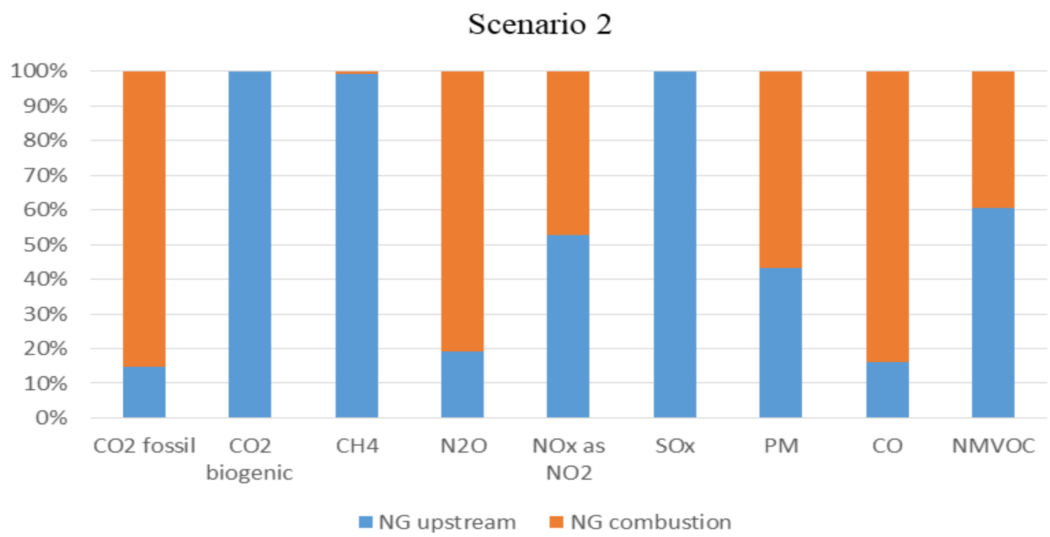


Figure 5.7 Scenario 2: Pollutant emission contributions by life cycle stage.

Scenario 3 considered biomass as the only fuel used for district heating at UBC campus to meet energy demand of 1,011 TJ per year. This implies a larger amount of wood (as calculated and presented in Table E2-3) to be processed and delivered to UBC. While 68.8% of emitted GHG (2.62E+06 $kgCO_{2eq}$) is attributed to the gasification stage with mainly biogenic emissions, wood transport (1.12E+06 gCO_{2eq}) shares 29.4% GHG emissions and wood processing (6.69E+04 $kgCO_{2eq}$) is responsible for remaining 1.8% and (Figure 5.8).

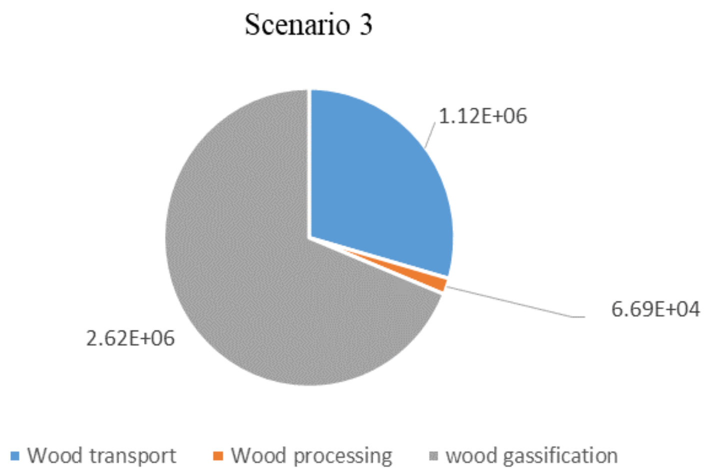


Figure 5.8 Scenario 3: Annual GHG emissions [$kgCO_{2eq}$] per life cycle stage for biomass.

The total amount of emitted GHG, here calculated to be 3.81E+06 kg CO_{2eq} (Table E2-3), is one order of magnitude smaller than in Scenario 2 where total annual GHG of 7.08E+07 kg CO_{2eq} were emitted when the same amount of energy was produced solely by natural gas. The complete replacement of natural gas with wood waste could therefore annually reduce GHG emissions for 67 $ktCO_{2eq}$ which is more than 90 % reduction in GHG emissions.[26]

One of the major contributors to GHG, CO_2, is released wherever fossil fuels are used such as for wood transport and wood processing with equipment utilizing diesel. Wood processing also contributes to emissions of CH_4, CO and SO_x, but emissions of CH_4, SO_x and CO also come from transportation. The portion of the emitted pollutants are biogenic in nature which helps to minimize GHG emissions and global warming impacts.

[26] 1 kilogram [kg] = 1.00E-06 kiloton (metric) [kt].

Pollutant contributions to emissions by process stages for scenario 3 are depicted in Figure 5.9.

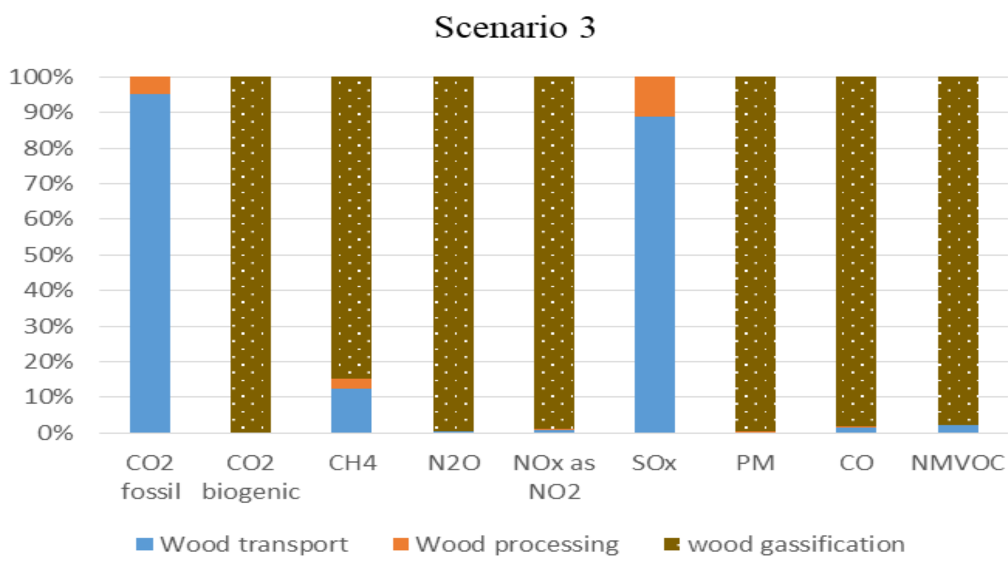


Figure 5.9 Scenario 3: Pollutant emissions contributions over different life cycle stages.

To address uncertainty, a sensitivity analysis was performed by changing the wood waste transport distance. When the distance was set to be 150 km per trip instead of 78.8 km per trip (27.2 km per trip from industry to Cloverdale and 51.6 km per trip from Cloverdale to UBC), GHG result just for transportation segment doubled, from 1.12E+06 kg CO_{2eq} to 2.13E+06 kgCO_{2eq} (Figure 5.10). The gasification stage still remained the main contributor to GHG mainly by N_2O and biogenic emissions of CH_4 (see Table E2-4). The reduction of GHG compared to scenario 2 is 98.37 ktCO_{2eq}, implying that increased transportation distance added 1.01 ktCO_{2eq}/year.

Scenario 3: total transportation changed to 150 km

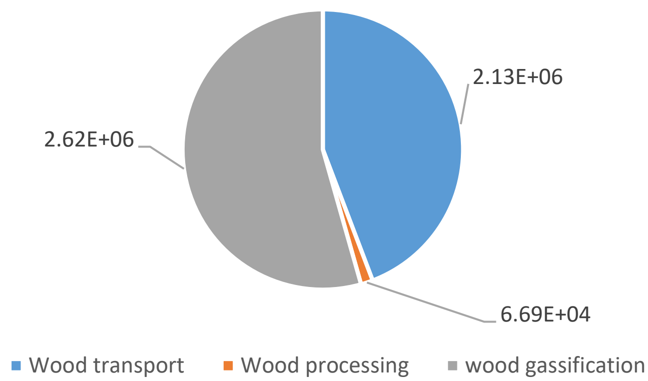


Figure 5.10 Scenario 3: Annual GHG emissions [$kgCO_{2eq}$] per life cycle stage for biomass with increased transportation distance.

5.3.2. Impact assessment approach 2

All energy consumption, emission data for unit processes and transportation (related to energy and fuels production and use) were input into SimaPro software for analysis. Impact assessment was conducted using IMPACT2002+ v 2.12 methodology. The focus of this assessment is global warming. Mid-point is a convenient impact category as further pathway (damage categories) may be associated with higher uncertainties (Olivier et al., 2003), although they are being commonly used in a number of studies (Pa et al., 2011; McManus, 2010), and lately with improved assessment methods (Weldu et al., 2017; Notter, 2015).

Characterization factors (CF) for *global warming* reflects only the emissions into the air. A separate damage category *climate change* is identical to global warming midpoint and also expressed in [$kgCO_{2eq}$/kg]. The version of SimaPro used in this study (8.2.0.0) included IMPACT 2002+ assessment methodology with GWP for 500-year time horizon so the method was adapted for this study with a 100-year time horizon for global warming potentials. GWP presented in the IPCC 5th Assessment report (IPCC, 2013), and suggested in IMPACT2002+ User Guide (Quantis, 2012), for fossil CH_4 characterization factor (CF) of 27.75 kg CO_{2eq} /kg and for biogenic CH_4 of 25 kg CO_{2eq} /kg to reflect the fact that CO_2 produced from biogenic CH_4 in the atmosphere is neutral.

LCA method is generally more appropriate for evaluation of global impacts since generic characterization factor, and therefore iF, represent average conditions (such as population density) of a broader area or a region, therefore the method is not sensitive to variation of site-specific local conditions for accurate assessment of community-related impacts such as exposure and human health. Thus, impacts related to global human health were not evaluated by this method since the local health impacts have been already covered in Chapters 3 and 4 of this study. Mid-point results for global warming/climate change comparing the three selected scenarios in this study are presented in Table 5.4.

Table 5.4 Mid-point impacts for annual energy output of 1,011 TJ at UBC Point Grey campus.

Mid-point Category	**Units**	**Scenario 1: NG, oil and biomass**	**Scenario 2: NG, oil**	**Scenario 3: Biomass**
Global warming	kg $CO_{2\ eq}$	6.18E+07	7.57E+07	1.95E+06

It should be noted that both upstream and downstream processes are included in the life cycle analysis. However, since biomass was utilized from local sources as waste wood, stages such as harvesting and long-distance transportation are avoided, which could be noticeable contributors to overall impacts (Pa, 2010). Utilizing locally sourced wood waste can reduce GHG emissions by approximately 97% compared to heat produced by natural gas only or a combination of natural gas, fuel oil and biomass.

The use of biomass in combination with natural gas and oil (Scenario 1) lowers the global warming impacts which would otherwise be more significant in case of only fossil fuels utilization (Scenario 2). The use of biomass in Scenario 3 achieves noticeable reductions in global warming impact from 7.57E+07 to 1.95E+06 kg CO_{2eq} compared to the use of natural gas only.

Previous case studies for UBC campus heating (Pa, 2010) reported GHG emissions reduction between 79% and 83% when fossil fuels are replaced with biomass. The previous study, however, considered upstream emissions from harvesting and sawmill operation, used longer transportation distances for wood residues delivery to UBC which could have added to GHG emissions, and estimated BRDF emissions as the plant was not built yet. In addition, the study considered different period with calculation based on total energy demand equal to 974 TJ. This study used actual performance data for fuel consumption for both plants and the 2012-2013 period of operation with 1,011 TJ energy produced.

As most LCA studies confirmed, when biomass replaces fossil fuels, a significant net reduction in GHG could be achieved (Cherubini and Strømman, 2011). A study by Parajuli et al. (2014) evaluated DES in Denmark where straw was used for district heating. They found the reduction of GHG[27] to be 187g/CO_{2eq} per MJ heat production when gasification technology is used instead of combustion. A review (Patel et al., 2016) which compared biomass conversion technologies for energy production outlined studies where 8.8 to 10.5 gCO_{2eq} was achieved as the reduction in GHG emissions per MJ of energy produced in case of CHP gasification and 80 -110 gCO_{2eq}/MJ in case of biomass combustion for heat only production. A Finish study (Havukainen et al., 2018) which investigated small-scale biomass CHP, concluded that the replacement of fossil fuels with biomass for heat production can result in 59–66 g$CO_{2eq.}$/MJ energy reduction with biogenic emissions included. The findings are in line with this study where reduction of GHG of 66 gCO_{2eq}/MJ heat production is estimated for total replacement of natural gas by biomass. It should be noted that different boundary framework, different softwares (such as GREET, SimaPro, TEAM, GHGenius, GaBi) are used across studies along with different impact assessment methods so direct comparison may be a challenge.

5.4 Conclusion

The release of greenhouse gasses into the atmosphere is responsible for global atmospheric warming and consequently the changes of Earth's climate. One of the major contributors to greenhouse gas emissions in BC is energy sector. In this study assessment of greenhouse gas emissions from a district heating system at the UBC campus was studied. Three scenarios were considered: Scenario 1, the base case scenario as existed in 2012-2013 where 80% of base load system produced energy by natural gas combustion at the Power House with an addition of a small peaking demand met by fuel oil and approximately 20% was supplied by a biomass

[27] Study (Parajuli et al., 2014) uses different GWPs for CH_4 (25) and N_2O (298) for a 100-years horizon than this study which used GWP for CH_4 fossil (27.75) and N_2O (265) for both assessment approaches.

gasification plant. Scenario 2 considered the same annual energy demand but met only by natural gas, whereas scenario 3 investigated global impacts in terms of GHG emissions in case that the whole energy demand was met by biomass gasification plant on campus. Upstream and downstream life cycle stages were considered for the production and use of natural gas and oil whereas only collection, transportation and use stages were considered for biomass with wood waste collected locally.

It was concluded that the total amount of emitted GHG from Scenario 3 (3.81E+06 kg CO_{2eq}) is one order of magnitude smaller than in Scenario 2 where total annual GHG of 7.08E+07 kg CO_{2eq} were emitted when the same amount of energy was produced solely by natural gas. The replacement of natural gas with wood waste could therefore reduce GHG emissions for more than 90% in case of wood waste being sourced locally. The analysis of stage-wise emissions per pollutant in case of natural gas being the only fuel used (Scenario 2) indicted that the major contributor to CO_2, N_2O and CO emissions is natural gas combustion whereas upstream processes are less intense in emissions and are associated with emissions of CH_4, NO_x, SO_x and NMVOCs. Scenario 3 with biomass indicated that CO_2, a major contributor to GHGs, is released wherever fossil fuels are used for wood residue processing and transport. Increasing transportation distances from 78.8 km to 150 km for biomass scenario could double GHG emissions from transportation segment and add 1.01 kt per year of GHG to the atmosphere.

Chapter 6: Economic valuation of district heating options

6.1 Introduction

Air pollution costs global economy more than US $5.11 trillion in welfare losses each year. This metrics incorporates costs associated with health and consumption. Monetized losses due to absence from work (lost income) alone cost global economy US $225 billion annually (The World Bank and Institute for Health Metrics and Evaluation, 2016). North America's welfare losses are 3% of GDP,[28] 2013 equivalent, while at the same time the greatest losses are in East Asia and the Pacific where costs of premature death from air pollution reached 7.5% of GDP.

Policy actions in many countries which target air pollution reduction focus primarily on reduction of greenhouse gases (GHG) and fossil fuels. Systematic literature review by Akhtari et al. (2014) emphasizes policies and government incentives such as CO_2 taxes and tradable carbon credits as ones which can play a substantial role in making biomass an attractive choice for district heating. Economics of a variety of GHG abatement options including biomass as a fuel to replace fossil fuels is extensively covered in literature.

An Austrian study (Kalt and Kranzl, 2011), suggested that the abatement costs associated with GHG mitigation and fossil fuel replacement will depend on the technology selection, feedstock type, plant size and site-specific combined heat and power (CHP) plants operating conditions. The authors showed that when oil-fired boilers and gas-fired heat generating plants are being

[28] GDP – Gross Domestic Product.

replaced with wood-based heat generating technologies abatement costs ranged from - 45 €/t CO_{2eq} (– 11 €/MW_{h-HHV}) to 93 €/t CO_{2eq} (24 €/MW_{h-HHV}), respectively. The authors concluded that using biomass for the heat generation and CHP are the most cost-effective solutions for Austria in terms of GHG mitigation and fossil fuel replacement. In addition, the study showed that wood-based heating systems are more economic and have a lower GHG abatement cost if they operate at the higher annual operating hours at the full load. Heating systems with 50 kW capacity have the best economic efficiency (€/t CO_{2eq}).

Another study conducted in Portugal estimated 17,981 t CO_{2eq}/year avoided emissions in case of investing in biomass power plants based on dedicated energy crops. However, the financial viability for such projects may be difficult to estimate as the costs for energy crops supply chains could be higher than for the power plants (Carneiro and Ferreira, 2012).

Some costs of air pollution have not been included regularly in economics of technology selection, such as external costs or externalities (Li et al., 2015). One of the most important externalities is human health which when monetized can demonstrate a burden of disease caused by air pollution impacts and costs due to morbidity or premature deaths. Economic valuation of human health can well express the interest of a society for trade-offs (what people are willing to give up in alternative to choices related to consumption) for benefits in environmental quality (Bell et al., 2008). For example, reducing daily average $PM_{2.5}$ levels to prescribed air quality (AQ) standards in China could reduce emergency departments visits and deaths from respiratory diseases for 23 - 42 M yuan (approximately \$4.4 to 8.2 M)[29] and 25 - 670 M yuan (approximately \$4.9 to 130 M) per year in 2015 yuan, respectively (Chen et al., 2017). A non-monetized approach such as physical health impact indicator DALY (Disability-Adjusted Life Year) is highly recommended (Bachmann and van der Kamp, 2017) for policy communication and quantified in many studies related to biomass applications (Jana and De, 2017; Martenies et al., 2015; Pa et al., 2013; Perilhon et al., 2012; Pa et al., 2011).

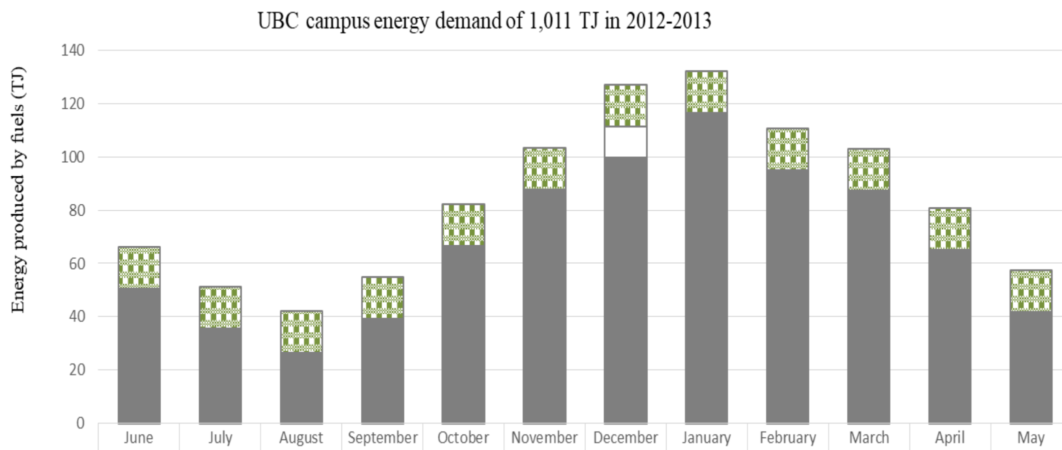
The objective of this chapter is to estimate the Net Present Value (NPV) of the biomass district heating system so to evaluate if a sum of discounted cash flows associated with considered benefits (savings in taxable GHG emissions, avoided fossil fuel procurement costs, etc.) overweight cost associated with such system (e.g. new capital investment, variable operational and maintenance costs, wood fuel costs). Costs and benefits of health-related impact are also discussed.

6.2 A summary of reported UBC district heating costs and GHG emissions

As mentioned in Chapter 4, energy production to meet the UBC campus energy demand for the base year of 2012-2013 was calculated to be 1,011 TJ comprising of natural gas for base load and fuel oil for peak load. In addition, BRDF (Bioenergy Research Demonstration Facility) started operation contributing approximately 20% of total energy production in that year. During the first year of BRDF operation, steam production from BRDF was reported to be 148,920 KLBS which corresponds to 188 TJ of thermal energy. A 100% plant's uptime as a very

[29] \$ denotes Canadian dollars; \$1M denotes \$1,000,000; \$1K denotes \$10,000.

conservative approach and equal monthly steam production are assumed in this study. During the same period, a total of 907 TJ energy was produced by PH, with 893 TJ using natural gas for base load and almost 14 TJ from fuel oil for peak load over the period of December 2012. (Figure 6.1).



	June	July	August	September	October	November	December	January	February	March	April	May
Energy from biomass [GJ]	15,671	15,671	15,671	15,671	15,671	15,671	15,671	15,671	15,671	15,671	15,671	15,671
Energy from peak oil [GJ]	0	0	0	0	0	0	11,417	0	0	0	0	0
Energy from NG [GJ]	50,345	35,684	26,465	39,397	66,430	87,712	99,863	116,537	94,930	87,521	64,999	41,665

Figure 6.1 Energy demand for the UBC campus in 2012-2103.

The total thermal capacity of BRDF is 5.8 MW_{th} from steam and 2.8 MW_{th} from heat recovery when operating in heating mode, and 1.96 MW_{el} when operating as CHP (UBC, 2015a). This implies that at the full capacity BRDF can generate 75,336 MWh_{th} or 271 TJ[30] of heat annually. Based on the latest UBC report (UBC, 2017), the use of natural gas (and therefore UBC's costs) is decreasing since 2015 whereas the use of biomass slightly increased. That could likely be attributed to the new ADES (Academic District Energy System) project and more efficient use of fuel.

[30] 1MW_h = 3.6 GJ; I TJ = 10E+03 GJ.

6.3 Economic valuation methodology

A simplified economic analysis presented here is solely based on the biomass conversion at the UBC campus and only for thermal mode. Input data were obtained from UBC reports (Wauthy and Giffin, 2017; UBC, 2015b; UBC, 2014; UBC, 2011; UBC, 2010), and literature sources. All available costs reported were summarized, input in MS excel spreadsheet as capital cost and operational and maintenance cost (O&M) so future values (FV) were calculated for the assumed 20-year life period of the considered plants (NREL, 2016). An annual inflation rate of 2.04% was used based on the Bank of Canada[31] historic data as a 10-year average with a commercial interest of 6.5% adjusted for inflation[32] to give an effective interest rate of 4.37%. Since the focus of this part of study (Chapters 5 and 6) is GHG emissions and costs and benefits related to abatement of GHG emissions, for calculating the present value, PV (2012 $), of operating costs the following equation was used (Field and Olewiler, 2005):

$$PV = \sum_{n=0}^{n=20} (OMn)/\,(1+r)^n \qquad (6\text{-}1)$$

Where:

PV is the present value of annual costs,

OMn is the total operational and maintenance cost for period n, referring to thermal mode,

r is the effective commercial interest rate adjusted for inflation,

n is the time period (n = 0 for 2012 and n = 20 for the end of life time).

[31]Source: http://www.bankofcanada.ca/rates/indicators/capacity-and-inflation-pressures/inflation/historical-data/ (Accessed August 28, 2016).

[32] Source: http://www.calculatorsoup.com/calculators/financial/investment-inflation-calculator.php (Accessed August 28, 2016).

The base year for assessment (n=0) is 2012 and different operational options were considered as specified in section 6.4. Additional economic analysis was performed to discuss external costs which refer specifically to air pollution.

6.3.1. Assessment of costs and benefits associated with the development, operation and maintenance of biomass-based district heating at UBC

BRDF was constructed in the period 2010 - 2012 and became operational in 2012. The construction was completed on time with the contribution of the following funding sources: Sustainable Development Technology Canada, NRCan - Canadian Wood Council, NRCan Clean Energy Fund, BC Bioenergy Network, FP Innovations/Ministry of Forests, BC Innovative Clean Energy Fund, Western Economic Diversification, Nexterra (In kind), UBC Building Operations/Energy and Water Services.

Capital investment for building the BRDF was reported to be $27.4 M.[33] It included Nexterra plant equipment procurement and installation (roughly $16.4 M), plant building construction (over $5M), utilities connections, planning and design fees, permits, insurance, project management, retained risk fee. However, since only thermal mode was considered in this study some assumptions are made below along with a summary of parameters used in calculations:

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[33] Planned budget was $26M (UBC, 2010).

a) Capital cost of the equipment associated with thermal mode is estimated to be \$8.2 M and this cost was used as capital cost in the calculation, which is 50% of the capital cost for the CHP Nexterra equipment.

b) Total capital cost for heating mode, TCC_h, (including the building and other costs cited above) used in calculations is \$19.2 M obtained by subtracting the engine cost:

$$TCC_h = \$27.4\ M - (\$16.4\ M/2) \tag{6-2}$$

c) Annual operation and maintenance cost (O&M) during the first year of BRDF operation was estimated as 5% (Delivand et al., 2015) of the TCCh cost which is \$96 K.

d) The delivered cost of biomass is \$69/ODMT (\$62/OMDT+GST+PST) in 2012 cost as contracted and supplied by Cloverdale. In addition, as a public sector organization UBC pays carbon offsets[34] on all commodities including biomass (only for CH_4 and N_2O emissions) at \$0.06/GJ (for emission factor of 2.24 kg CO_{2eq}/GJ for wood fuel) whereas carbon tax is only paid for natural gas (Wauthy and Giffin, 2017; UBC, 2010).

e) All-in cost of fossil fuel of \$10.47/GJ included the cost of fossil fuel delivered and all taxes (equal to \$7.72/GJ), cost of carbon tax of \$1.5/GJ and carbon offset of \$1.25/GJ (for natural gas GHG emission factor 49.87 kg CO_{2eq}/GJ for combustion only), (Wauthy and Giffin, 2017; UBC, 2010).

f) Since there were no new capital investments in the PH, capital cost will remain equal for both options considered in economic assessment and therefore it was excluded in comparison for simplicity; this postulation does not impact the difference in total cost among scenarios.

[34] Carbon taxes of CAN \$30/t CO_{2eq} are paid according to the Carbon Tax Act and Carbon Offsets of \$25/t CO_{2eq} are purchased according to the Carbon Neutral Government (CNG) Regulation.

g) Ash generation is 119 t/year but 50% is used on campus whereas the other 50% is disposed at a cost of $100/t which equals $5,950 annually (UBC, 2010).

h) Fuel consumption used in this analysis for all scenarios is calculated in Chapter 4.

Economic parameters used in the current analysis are summarized in Table 6.1 below.

Table 6.1 Economic parameters.

Parameter	Value
Capital investment	
a) Capital cost for Nexterra equipment for thermal mode [$]	8.2 M[35]
b) Cost of land, building construction, installation, permits) [$]	11 M
Operating and Maintenance (O & M)	
Maintenance [$/year]	96 K
Fuel biomass [$/ODMT+taxes]	69
Carbon offset purchase for wood fuel [$/$GJ_{input}$]	0.06
All-in fuel natural gas cost [$/$GJ_{input}$][a]	10.47
Ash disposal [$/t]	100
Operators' salary [a] [$/year]	60.2 K
DHS useful service life [year]	20
Annual inflation rate [%]	1.88
Nominal commercial interest rate [%]	6.5
Effective commercial interest rate adjusted for inflation	4.37
Equipment depreciation rate [%]	30

[a] Source: (UBC, 2010), basic NG price based on 3-year average.
[b] Source: http://www.fin.gov.bc.ca/tbs/tp/climate/A4.htm (Accessed October 8, 2017).

As for the steam plant power house (PH) total O&M costs for base year (2012) were $2.9 M.

6.4 Results and discussion

The following options are considered:

[35] Cogen plant was sold as package with a fixed price of $16.4 M from Nexterra. Thermal mode only specification was not available so 50% of total cost was assumed.

A) Operation of only PH where natural gas was used to meet energy demand of 1,011 TJ for 2012. Since the building and equipment already existed, no capital investment was considered in this case. Fuel all-in costs for meeting entire energy demand were estimated to be $11.9 M out of which $3.1 M was spent on carbon costs alone.

B) Operation including both PH and BRDF as of 2012 (scenario 1 in previous chapters) where 822,965 GJ was produced by PH and 188,061 GJ by BRDF requiring 9,304 ODMT of wood which costed $64.2 K; $1.7 K was spent on purchased carbon offsets; in addition, all-in fossil fuel costs were $9.6 M out of which $2.5 M was spent on carbon taxes; Capital cost for the BRDF (heating mode only) of $19.2 M was included in total costs.

The main calculated costs are summarized in Table 6.2. Present value was calculated for each option, for option A only O&M costs and for option B total PV included capital cost and O&M costs. For option A where only O&M were considered due to already existing PH infrastructure, annual O&M was $14.8 M and calculated total PV $209 M. For option B, capital cost of $19.2 M was added to O&M PV of 208.7 M which resulted in a total PV for this option of $227.9 M.

Table 6.2 Summary of calculated parameters [in $2012].

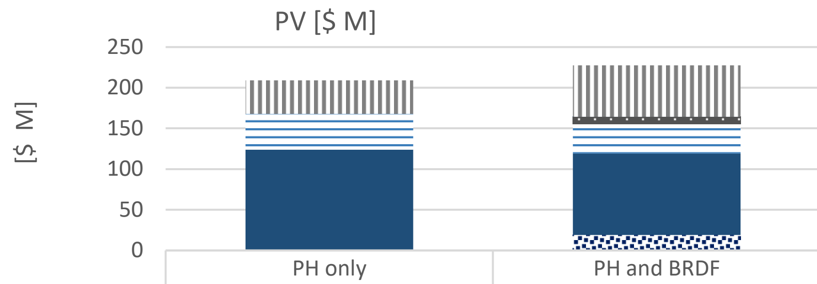
Parameter	**Option A**	**Option B**	
	PH only	**PH and**	**BRDF**
Annual energy output [GJ]	1,011,026	822,965	188,061
Annual energy input [GJ]	1,133,232	918,332	276,560
Annual fuel cost [$/year]	8.7 M	7.1M	64.2 K
Annual Carbon Tax [$/year]	1.7 M	1.4 M	0
Annual Carbon Offset [$/year]	1.4 M	1.1 M	1.7 K
Annual other O&M costs [$/year]	2.9 M	4.5 M	
PV (O&M) cost[a] [$]	209 M	208.7 M	
Capital cost	-	19.2 M	

[a] There are other O&M parameters (like ash disposal, salaries, maintenance etc.) which are included in calculation but not presented in this table.

With respect to O&M costs, option A included fuel costs and carbon costs which for natural gas included a carbon tax of \$30/t CO_{2eq} and a carbon offset of \$25/t CO_{2eq}. With an addition of BRDF to DES, as in option B, costs associated with carbon tax are avoided for the portion of biomass used (about 20% of heat generated). However, since old steam power plant PH was still producing about 80% of heat, high O&M costs associated with aging PH were still substantial. Option B also had a substantial capital expenditure due to new BRDF infrastructure, resulting in total PV of \$227.9 M.

The economic impact of introducing biomass in DES can be demonstrated through the Net Present Value (NPV), calculated as the difference between options A (NG only) and option B (combined NG and biomass). The net present value (NPV) between options A and B is \$ -18.9 M which indicates that the introduction of a biomass plant (option B) increased the cost of district heating at UBC campus.

With the parameters as selected in this study, the results in Figure 6.2 show that carbon tax and carbon offset are dominating the life cycle costs followed by the O&M costs which are higher for option B due to combined costs for both plants. The use of wood fuel leads to savings in carbon offsets and carbon tax (which indicates benefits of introducing biomass), because carbon offset is much higher for natural gas (\$1.25/GJ) than for biomass (\$0.06/GJ). Savings in carbon taxes is an incentive that can support biomass based DES providing that other conditions and associated costs are well justified.



	PH only	PH and BRDF
PV Other O&M	41	63
PV Carbon cost biomass	0	0.23
PV Biomass fuel	0	9
PV Carbon cost NG	44	36
PV Fosill fuel cost	124	100
Capital cost	0	19

Figure 6.2 Cost breakdown for two DH options at UBC.

A techno-economic study was carried out in Italian context (Arena et al., 2010) to evaluate two design configurations of a biomass-to-energy small scale plant. It concluded that the variation in biomass cost is less important than all-inclusive feed-in tariff which crucially affects economic parameters such as averaged discounted cash flow. However, the authors emphasized that site-specific variables such as heat demand and the costs of the waste treatmant and disposal should be taken into consideration. Another study (Börjesson and Ahlgren, 2010) evaluated cost-effectivness of different applications of biomass gasification and found that CHP plant is a cost-competetive choice in situations of high heat demand. An important parameter is the availability of local low-cost biomass. A North American study by Young et al. (2018), investigated driving factors for small scale biomass applications in 3142 counties. Among the most important are

Heating Degree Days (HDD),[36] natural gas processing and available biomass as well as regional government initiatives and national financing policies.

6.4.1 Addressing uncertainty

Economic estimates are associated with a number of uncertainties which range from fuel prices to inflation rates. To address uncertainty in fuel price, natural gas prices were analyzed from historical trends to forecasted prices. Historical data show that natural gas reached the highest price in December 2005 of US $15.39/MMBtu (equal to US $13.8/GJ).[37] Forecast data predict an increase in the next few decades. For example, based on EIA forecast for Henry Hub as presented in Wauthy and Giffin (2017), natural gas price can increase to $12/GJ by 2035. If other parameters are kept the same as previously explained, the all-in price for natural gas would come to $16.19/GJ which is an increase of 35% compared to current price. This increase will affect total cost over plant life time resulting in a present value of $301M for option A (natural gas only) and $302 M for option B (combined NG and biomass). It appears that an increase in natural gas price alone can bring total costs of option A close to option B.

Sensitivity analysis was also performed to investigate how carbon tax changes would influence the PV of proposed operating scenarios at present fuel prices. In 2016 Government of Canada proposed a carbon pricing framework to reduce GHG emissions and grow green economy (Canada, 2017). By 2022 price should reach $50/t CO_{2eq}. This amount was used to re-evaluate

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[36] HDD is the number of degrees [ºC] that a day's average temperature is below 18 ºC indicating that a building requires heating; this metrics quantifies energy demand. Source: https://www.investopedia.com/terms/h/heatingdegreeday.asp (Accessed April 5, 2018).

[37] Source: https://tradingeconomics.com/commodity/natural-gas (Accessed March 30, 2018). 1 MMBtu = 1.055056 GJ.

presented scenarios. Since carbon tax is applied only to natural gas, it will result in an all-in price of \$11.47/GJ provided that other price components remain unchanged. It was found that an increase of \$20/t CO_{2eq} in carbon tax from the current \$30/t CO_{2eq} will increase the PV by \$16 M (to \$225 M) for option A but only \$13 M (to \$241 M) for option B which indicates benefits in the form of saved expenditures on carbon tax when biomass was replacing fossil fuel even partially. It appears that savings in carbon taxes at a higher tax rate will offset part of the capital investments for bioenergy plant.

6.4.2 Trade-offs associated with the selection of district heating options

Switching to biomass for district heating applications have numerous advantages, the reduction of GHG and consequently global warming, and savings in carbon-related taxes as demonstrated by this study (Chapters 5 and 6). At the same time, local air quality and human health may be compromised due to proximity of a biomass plant to local population (Chapter 4).

External costs of selected pollutants are presented in Table 6.3. External costs are taken from Pa et al. (2013), and total emissions are calculated in this study and presented in Tables E2-2 and E2-3. Since health impacts are more of a local character, only emissions from the plants were considered. Biogenic CO_2 from wood combustion is assumed to have zero contribution to net GHG emissions as previously explained. It should be noted that both generic and biogenic components of CO and CH_4 were taken into account although biogenic components of these compounds have slightly lower impacts on climate change. Here, emissions of each CH_4 and CO are presented as a sum of each compound's generic and biogenic component, so external costs for these compounds were assumed to be an average value of their respective components' values.

Calculations indicated that the total annual external costs for option A (when PH is operational only) is $2.08 M/year and $29 M over plant's life time, most of which, over $25 M is attributed to CO_2. An addition of biomass to natural gas for DES (option B) decreases external costs to $25.7 M over plant's life time (which could be considered as benefits) with $20.5 M attributed to CO_2 solely.

Table 6.3. Summary of externalities for district heating options at UBC

Pollutant	$/kg emitted	Option A [kg/year]	Option A [$/year]	Option A PV[$]	Option B [kg/year]	Option B [$/year]	Option B PV [$]
		NG	NG	NG	NG+biomass	NG+ biomass	NG+biomass
CO_2 fossil	0.032	5.57E+07	1.78E+06	2.52E+07	4.45E+07	1.42E+06	2.02E+07
CO_2 biog.	-	-	0.00E+00	0.00E+00	2.50E+04	0.00E+00	0.00E+00
CH_4	0.24	1.07E+03	2.57E+02	3.64E+03	2.58E+04	6.18E+03	8.75E+04
N_2O	4.5	1.02E+03	4.59E+03	4.59E+03	2.38E+03	1.07E+04	1.51E+05
NO_x as NO_2	5.23	4.64E+04	2.43E+05	3.44E+06	5.75E+04	3.01E+05	4.26E+06
SO_x	4.01	0.00E+00	0.00E+00	0.00E+00	6.24E+03	2.50E+04	3.54E+05
$PM_{2.5}$	25.60	8.82E+02	2.26E+04	3.20E+05	8.97E+02	2.30E+04	3.25E+05
CO	0.68	3.90E+04	2.65E+04	2.57E+04	3.53E+04	2.40E+04	3.40E+05
NMVOC	1.47	2.55E+03	3.75E+03	5.31E+04	3.24E+03	4.76E+03	6.74E+04
SUM	4.17E+01	5.58E+07	2.08E+06	**2.90E+07**	4.47E+07	1.82E+06	**2.57E+07**

Analysis per pollutant (Figure 6.3) revealed that the largest externalities are emissions of fossil CO_2 from natural gas burning, \$1.78 M/year if all energy demand is met by natural gas (option A). This cost could be interpreted as a monetary damage due to global warming from the combustion of natural gas (base load).

Introduction of biomass to DES (option B) resulted in decrease of total costs associated with CO_2 emissions to \$1.42 M/year, and savings of \$5 M over plant's life time. While biomass has a benefit in terms of global warming, emission of fine particles and nitrogen oxides are of concern for local air quality and human health. \$2.26 K/year could be the expected costs for human health impacts from fine particulate emissions from natural gas combustion, whereas those costs for fine particles increase to \$2.30 K/year when biomass on-site gasification plant is operational in addition to PH (option B). On a 20-year (plant life time) basis, expected costs for human health impacts due to $PM_{2.5}$ emanations could be \$32.00 K and \$32.50 K for natural gas (option A) and natural gas and biomass (option B), respectively. Since uncontrolled NOx emissions from biomass use are higher than from natural gas, external costs are also around 20 % higher for option B where biomass was introduced in addition to fossil fuels (\$30.10 K/year) than the natural gas only scenario (\$24.30 K/year). On a 20-year basis, NOx external costs from natural gas were estimated to be \$3.44 M and \$4.26 M from combined natural gas and biomass option. These pollutants would make impact on local air quality and fine particulates in particular should be of concern with respect to human health impacts.

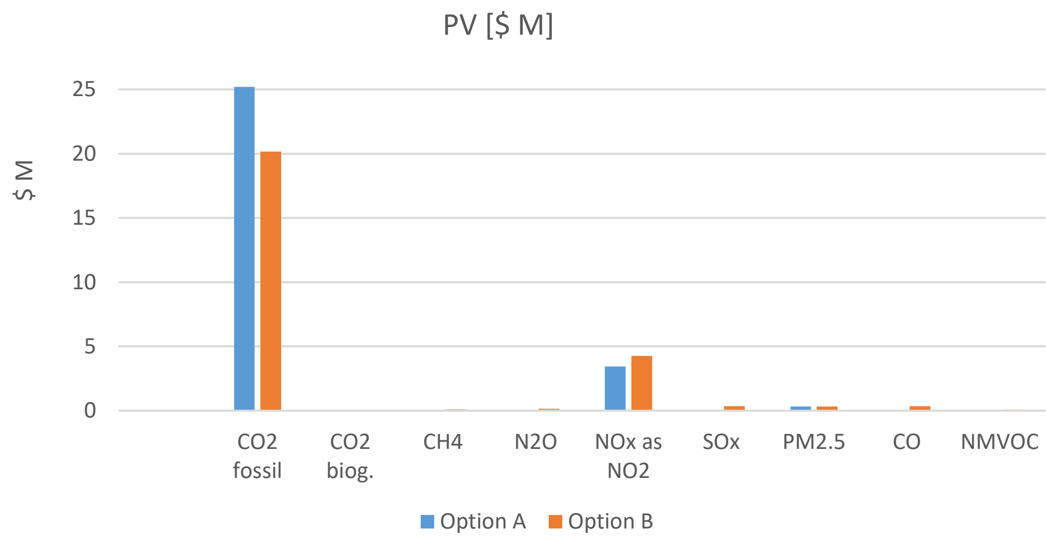

Figure 6.3 External costs for option A (natural gas only) and option B (natural gas and biomass) for the period of plants' life time.

It appears that both technologies have advantages and shortfalls when it comes to emissions and impacts. Even when emissions are monetized, the same conclusions appear to be valid for trade-offs between these two options as the ones presented in Chapter 4: biomass is a superior choice when global impacts especially global warming and consequently climate change are of primary concern. Policy incentives of non-taxable emissions originating from renewable sources favor such outcome. However, caution should be exercised with choosing the location in order to minimize population exposure to air pollutants. On the other hand, fossil fuels, natural gas in particular as a clean-burning fossil fuel would impose less local impacts but will cause damages to the global environment in terms of global warming and climate change.

The following table (Table 6.4) summarizes the key findings with respect to DES options considered for UBC. The use of natural gas to meet UBC heat demand entirely could be a preferable choice in terms of impacts on overall community exposure as IS can increase with the addition of biomass mainly due to uncontrolled NO_x emissions but fine particles as well, at the current plant locations. However, introducing biomass could reduce life cycle GHG emissions by 12,490 t (17.6%) and total external costs over the plants' life time by more than $3 M which will contribute to climate change and global warming mitigation. On the other hand, total costs (over plants' life time) associated with the inclusion of biomass in DES expressed as total PV (capital and O&M costs) are higher by almost $19 M than the existing steam power plant run on natural gas.

Table 6.4 Summary of key findings on local and global impacts for UBC district heating options.

Parameter	**NG only (PH operational)**	**NG and biomass (PH and BRDF operational)**
∑ IS scenario [DALY]	495	513
Life Cycle GHG emissions [t CO_{2eq}]	70,809	58,319
Total PV [$]	209 M	228 M
Total PV externalities [$]	29 M	26 M

Note: highlighted are advantageous parameters.

This analysis points out the importance of including societal costs into analyses of DES. Typically, techno-economic analysis serves for decision making on technology choices and location selection (to minimize infrastructure and maintenance costs) neglecting the externalities which could inform decisions in order to better protect human health and the environment. For example, biomass-related projects give priority to location assessable for trucks to bring biomass, a spatial lot for truck maneuver, closeness to distribution system (steam or hot water), etc. Permit application requires assessment of air quality but does not require assessments in terms of location selection with least impacts to particular community. This study demonstrated that such analysis is important to avoid exposure to fine particles in the first place and should be equally and regularly evaluated along with techno-economic factors.

Attempt was also made to tackle a possible expansion of the existing BRDF as one of the options UBC is considering for meeting the University's Climate Action Plan (CAP) for GHG reductions goals of 67% below 2007 level by 2020. It appears that such option, where biomass would solely meet UBC's energy demand, may lead to increased costs (Appendix F).

6.5 Conclusions

It is widely accepted that many factors affect economics of biomass energy systems, but published studies only emphasized policies and government incentives such as CO_2 taxes and tradable carbon credits which can play a significant role in making biomass an attractive choice for district heating systems. Some social costs of air pollution, like health impacts, have not been regularly included in economics of technology selection and as such they are considered to be external costs or externalities. One of the objective of this study was to tackle economics as part of the assessment of biomass district heating systems as a third pillar of sustainability, in harmony with environmental (ecological) and social in a path towards sustainable development.

A simplified economic analysis which focused on operational and maintenance costs and fuel procurement was performed to obtain O&M PV and total PV which included capital investment of district heating system at UBC Point Grey campus. Economics of two options is considered following the assumptions from previous chapters of this study: an originally existed option with PH producing heat for the campus with energy demand as of 2012-2013 and an option (scenario

1 as named throughout the study) as it was in period 2012-2013 when most of the steam (for heat and hot water on campus) was produced by natural gas and peak fuel oil at PH and almost 20% steam by BRDF using biomass. It is concluded that an introduction of biomass to DES increased total costs (total PV included capital and O&M costs) by $19 M compared to existing PH although some savings in carbon tax were generated at $8.4 M over the period of plants' life time (20 years).

When externalities are considered, namely, assigning monetary values to air pollutants emitted at the site both by PH and BRDF, $26 K could be avoided annually and $3.3 M over plants' life time in terms of its societal damages[38] when switching fossil fuel use to combined use of natural gas and biomass. With respect to individual pollutant damages, $2.30 K/year and $32.50 K over plants' life time could be expected as external costs for human health impacts from fine particulate emissions from combined operation of an on-site biomass gasification plant and PH plant. The same combined operation resulted in $30 K/year and more than $4 M over plants' life time in external costs from uncontrolled NO_x emissions. These pollutants would make impact to local air quality and fine particulates in particular should be of concern with respect to human health impacts. Their respective external costs are lower for the natural gas operation originated solely from PH. Emissions of CO_2 from solely using natural gas (option A) would cost the society $1.78 M annually and more than $25 M over plants' life time. Savings of $5 M could be expected with an introduction of biomass to DES.

[38] Damages avoided represent benefits.

It appears that biomass is a superior choice when global impacts especially global warming and consequently climate change are of primary concern. However, caution should be exercised in choosing the location in order to minimize population exposure to air pollutants. On the other hand, fossil fuels, natural gas in particular, have less local impacts but they will cause more damages to the global environment in terms of global warming and climate change. A proper compromise or trade-off should be considered in developing such district heating systems, based on a careful evaluation of local air quality impacts and global impacts as illustrated in this study. Sustainable cities and communities call for sustainable solutions where all aspects must be evaluated and balanced. Inclusion of externalities could inform policy makers of damages that could not otherwise be acknowledged in a typical techno-economic analysis.

Chapter 7: Conclusions and future research directions

7.1 Conclusions and significance of the research

Local impact assessments of biomass-based systems on air quality and the resulting community exposure are still in its infancy. Very few studies started recognizing the importance of local and urban health impacts of near-by stationary sources. Due to either lack of data or project purposes, those previous studies relied on many assumptions and did not account for dynamic population changes and actual spatial and temporal variations of ambient air quality (Martenies et al., 2015), or relied on selected archetypal environments and emission sources. Systematic literature review identified that there has been a lack of appropriate and accurate impact assessment methodology for parameters with extensive variability on local scale, and lack of assessment of biomass-based DES impacts on local ambient air quality and human health based on methods with higher accuracy and inclusive of local, site-specific characteristics.

To address these knowledge gaps, a systematic study has been conducted with UBC BRDF bioenergy facility as a case to address the following research questions. (1). How would the inclusion of site-specific terrain, land use and microclimatic characteristics, variable population density and breathing rates improve accuracy of local air quality and population health impact assessment of community-based biomass energy systems? (2). How would an incremental increase of $PM_{2.5}$, NO_x and CO concentrations from investigated biomass DES contribute to local ambient air quality and population exposure? (3). How would life-cycle GHG emissions from the investigated biomass DES contribute to global warming? (4). Considering capital, operational and maintenance (O&M) costs and externalities, how would the introduction of biomass-based DES affect the economics compared to fossil fuel-based DES?

An analysis on local air quality and human health impact by varying the spatial distribution of receptors, population dynamics, temporal population dynamics, and diurnal variations in people's breathing rates revealed that when accounting for all local-scale variations, from actual population density (as opposed to averaged census data commonly used in assessments), to local spatial and temporal micro-climatological and local spatial orographical conditions at the biomass plant site, more realistic, site-specific results could be obtained. When the dynamic variation of all parameters is accounted for, the real dynamic nature of iF is captured. Neglecting microclimatic characteristics such as site-specific diurnal circulation patterns which influence pollutant dispersion or short-term variation of parameters on a local scale such as population dynamics may lead to underestimation of iF by more than 20%. This amplifies the importance of incorporating both spatial and temporal dynamics in estimating the exposure (i.e. iF) in assessing the health impact of district heating systems in densely populated areas.

The improved methodology was then applied to the UBC district heating system with 2012-2103 operation as the base case and two other scenarios when all demanded heat would be produced only by PH using natural gas and all heat would be produced by an expanded BRDF using biomass, respectively. The results showed that the health impacts from a biomass-based energy system installed with an efficient PM control device mainly resulted from the uncontrolled NOx emission, followed by PM and CO emissions, among all criteria air pollutants. The lowest iF for this option indicates the importance of the plant location relative to community setting where the smallest number of people would be affected by plant emissions since iF is mostly influenced by the number of people exposed. On the other hand, it appears that a distributed DES with combined NG and biomass may have an advantage over a centralized DES in terms of overall health impact. Depending on plant locations compared to the location of a single plant (like in case of PH), distributed DES may have lower overall health impacts compared to a single biomass energy supply system.

With respect to pollutant contributions to air quality and health risks, it was found that the overall incremental contribution of fine particles ($PM_{2.5}$) was at least one order of magnitude lower than the provincial air quality objectives (BCAQO). However, the maximum $PM_{2.5}$ emission from the natural gas fueled PH could adversely add to the already high background concentrations. Nitrogen dioxide (NO_2) emissions from the BRDF with no engineered pollution controls in place exceeded BCAQO in all seasons except during the summer. It should be noted that CALPUFF predictions could be lower than actual outdoor concentrations originating from the considered sources so regular measurements can provide better insights in possible concentration exceedances. The impact score, IS, was the highest for NO_2 (677 DALY) when biomass entirely replaced fossil fuels, and the highest for $PM_{2.5}$ (64 DALY) if all energy was produced by natural gas. Complete replacement of fossil fuels by one biomass plant can result in almost 28% higher health impacts (708 DALY) compared to 513 DALY when both BRDF and the PH are operational mostly due to uncontrolled NO_2 emissions.

Global impacts of emitted pollutants from BRDF and PH were investigated in terms of life cycle greenhouse gas emissions. It was concluded that the total amount of emitted GHG (3.81E+06 kg

CO_{2eq}) from Scenario 3 where the entire energy demand is met by biomass is one order of magnitude smaller than in Scenario 2 where total annual GHG of 7.08E+07 kg CO_{2eq} were emitted when the same amount of energy was produced solely by natural gas. The replacement of natural gas with wood waste could therefore reduce GHG for more than 90% in case of wood waste being sourced locally. The analysis of stage-wise emissions per pollutant in case of natural gas being the only fuel used (Scenario 2) indicted that the major contributor to CO_2, N_2O and CO emissions is natural gas combustion whereas upstream processes are less intense in emissions and are associated with emissions of CH_4, NO_x, SO_x and NMVOCs. Scenario 3 with biomass indicated that CO_2, a major contributor to GHGs, is released wherever fossil fuels are used for wood residue processing and transport. Increasing transportation distances from 78.8 km to 150 km for biomass scenario could double GHG emissions from transportation segment and add 1.01 kt of GHG annually to the atmosphere.

Economics of the original PH producing heat for the campus with energy demand as of 2012-2013 and an option (scenario 1 as named throughout the study) and the setting when most of the steam was produced by natural gas and peak fuel oil at PH and almost 20% steam by BRDF using biomass, was evaluated. It is concluded that an introduction of biomass to DES increased total costs (total PV included capital and O&M costs) by $19 M over the plants' life time compared to existing PH although some savings in carbon tax were generated at $8.4 M over the same period.

Introducing external costs into consideration, namely, monetizing emissions with respect to their impacts on global warming and human health, $26 K could be avoided annually and $3.3 M over the plants' life time in terms of societal damages when switching fossil fuel use to combined use of natural gas and biomass. With respect to individual pollutant damages, $2.3 K/year and $32.5 K over the plants' life time could be expected as external costs for human health impacts from fine particulate emissions from combined operation of an on-site biomass gasification plant and PH plant. The same combined operation resulted in $30 K/year and more than $4 M over the plants' life time in external costs from uncontrolled NO_x emissions. These pollutants would make impact to local air quality and fine particulates in particular should be of concern with respect to human health impacts. Their respective external costs are lower for the natural gas operation originated solely from PH. Emissions of CO_2 from solely using natural gas would cost the society $1.78 M annually and more than $25 M over the plants' life time. Savings of $5 M could be expected with an introduction of biomass to DES.

Overall, it appears that biomass is a superior choice when global impacts especially global warming and consequently climate change are of primary concerns. However, caution should be exercised in choosing the location in order to minimize population exposure to air pollutants. On the other hand, fossil fuels, natural gas in particular, have less local impacts but they will cause more damages to the global environment in terms of global warming and climate change. A proper compromise or trade-off should be considered in developing such district heating systems, based on a careful evaluation of local air quality impacts and global impacts as illustrated in this study. Sustainable cities and communities call for sustainable solutions where all aspects must be evaluated and balanced. Inclusion of externalities could inform policy makers of damages that could not otherwise be acknowledged in a typical techno-economic analysis.

7.2 Strengths and limitations of the research

This study contributes to knowledge by developing an improved impacts assessment methodology for community-based biomass plants which is suggested for use by city planners, regulators and public health practitioners. A special focus is on local impacts which were scarcely covered in literature as the majority of published studies covered high-level global impacts. Even though some studies indicated the importance of local impacts, inclusion of detailed local micrometeorology, population dynamics and varying breathing rates has not been covered before for district energy systems. This approach enabled locally obtained dynamic iF and demonstrated that developed site-specific characterization factor CF_{helth} may bring more accuracy in assessing local impacts compared to the CFs based on consensus data and other population density data averaged over a large area, e.g. the European continent available in commercial life cycle analysis software packages such as SimaPro. Therefore the method proposed in this study (Chapter 3) is among the few studies that offer the accurate impact assessment on local air quality and human health.

This approach could be generalized and applied to communities and regions with complex settings, microclimatic conditions and varying population density, such as Metro Vancouver and Lower Fraser Valley districts in order to accurately evaluate impacts of growing biomass district energy systems, protect human health and ensure air-shed planning within the ecological carrying capacity. By analyzing in-depth the local impacts of a community-based operational biomass plant at UBC (which was selected as a case study) utilizing a newly proposed improved impact assessment methodology, this study led the way for future impact assessment approaches. The study also contributes to higher accuracy in the global impact assessment by utilizing BC specific electricity mix and transportation data via GHGenius, a locally developed software ((S&T)^2 Consultants, 2013).

Finally, by covering, local, global, economic and social aspects of biomass-based DES, this study demonstrated that all sustainability pillars should be included in an integrated impact assessment, which is especially important for the future development as trade-offs may be needed in order to protect environment and human health in a cost-effective manner.

Since BRDF was constructed and became operational in 2012, data analyzed in this study were used with a number of assumptions due to the limited data on emission testing. In this study, plant uptime was considered to be 100% and monthly steam production to be equal over the period 2012-2013 so to keep consistency in calculations. This assumption is a conservative approach and has not impacted the results or methodological approach.

Emission estimates from BRDF and Power House relied on published emission factors such as US EPA which are described as factor of varying quality in terms of number of measurements they were drawn from so those factors carry inherited uncertainties. Whenever needed, those factors were supplemented with ones published in literature originating from similar emission sources. Nevertheless, periodic emission tests at the plant were considered for comparison. The same applies for the ambient air quality tests which were available just from one station located on the roof of an adjacent building to monitor the impacts of emitted pollutants to buildings in close proximity of the plant. Measurements from one location present limitation in terms of further exploring local air quality based on monitoring data.

Life cycle assessment was carried out to quantify the global warming impacts due to the appropriateness of such methods for assessing global rather than local impacts. The importance of increased accuracy in assessment of local impacts associated with population exposure and health risks, which is the main strength and contribution of this study, is the main retraction in LCIA methodology so only global impacts were considered here using two approaches, both of which included foreground actual performance data wherever possible.

Economic analysis focused just on parameters that were of interest in this study, namely costs and benefits associated with GHG emissions and reductions; externalities were also covered based on monetized pollutant impacts from literature. The economic analysis does not include all costs and benefits associated with any of technologies but since the objective of this study is the consideration of GHG and airborne pollutants, the assumption does not affect the obtained results.

7.3 Future research directions

Impact assessment of biomass-based community energy systems with a focus on heat generation was studied here. The study resulted in a number of implications that could be further explored:

- Local air quality and human health risks due to exposure will largely depend on the plant's location. It appears that a distributed DES with combined NG and biomass may have an advantage over a community-based centralized single DES in terms of overall health impacts. Further research is needed to confirm the initial findings presented in this study and to explore impacts in cases of multiple locations and multiple plants on local air quality and population exposure.

- Indoor air quality, which is influenced by ambient air, could be of interest for further research with an addition of building specific parameters such as ventilation rate. People generally spend considerable time indoors and impacts of DES on indoor air quality has not yet been addressed comprehensively.
- An improvement in data availability with increased number of direct source emission tests as well as air quality monitoring at multiple locations would be important in future research which will aim at larger number of locally collected data while decreasing dependence on general average emission factors and other parameters. More site-specific characterization of emissions will increase public confidence and acceptance of DES and will change their perception about associated risks.
- This study presented the significance of locally obtained iF, but the future research could explore the inclusion of site-specific iF and CF_{health} in LCIA methodology which would bring more accuracy in local impact segment of life cycle assessments.
- Comprehensive assessment of sustainability in addition to consideration of environmental, social and economic aspects of technological solutions, embraces sustaining provisioning, regulating, supporting and cultural ecosystem services. Therefore, consideration of other bio-geophysical components should be addressed in future research so to comprehensively evaluate sustainability of energy systems which are fast growing in Canada and other countries and seem to present viable energy solutions for urban areas.

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Appendices

Appendix A Literature review

A.1 Literature search methodology

Literature search was based on mostly on electronic resources available from the University of British Columbia library. The following databases were searched to retrieve literature for this research:

- *Web of Science:* is an on-line database with multidisciplinary content updated weekly. It is linked to UBC for access of full text. http://resources.library.ubc.ca/page.php?id=138
- *Elsevier Science Direct:* is an on-line data base with full text articles from 3,800 journals, versatile in content. https://www.elsevier.com/solutions/sciencedirect.
- *PubMed*: is an on-line database containing articles in life sciences subject areas. It is produced by the National Center for Biotechnology Information (NCBI) at the U.S. National Library of Medicine (NLM) http://www.ncbi.nlm.nih.gov/pmc/; http://resources.library.ubc.ca/571
- *Google Scholar (GS):* An on-line un-restricted database containing a broad range of scholarly literature including peer-reviewed papers, theses, books, preprints, abstracts, technical reports. http://resources.library.ubc.ca/943

Search concepts such as, biomass, emissions, and health, as well as alternative terms for each concept, for example: for biomass I used: wood, forest residues, wood feedstock, were organized in an excel spreadsheet as a matrix. “Wildcards” were used where appropriate in order to retrieve variants on terms (e.g., wood*). Search terms were then combined using Boolean logic (AND, OR) to reduce the search results to those considered to be most relevant to the topic. The selection of retrieved material was restricted to those published since year 2000, unless older literature sources were of significant importance for understanding the later literature which builds on such baseline studies. Only articles and reports published in English language were considered.

Additional grey literature was searched by accessing: Intergovernmental Panel on Climate Change (IPCC)), (Environmental Protection Agency (US EPA), Natural Resources Canada (NRC), BIOCAP Canada, BC Bioenergy Network as well as recent media releases and professionally prepared reports for government of Canada or provincial governments. Some publications and articles were recommended by my supervisor and reviewers of draft articles I submitted for publishing.

Reference software and literature storage Bibliographic data for the obtained electronic literature was saved using online citation management software ZOTERO (http://www.zotero.org/) which enables access from other computers by its “sync” function. Additionally, electronic copies of cited literature were stored on the hard drive of my computer.

Articles selected for detailed consideration and inclusion in literature review were summarized in an excel spreadsheet to enable better understanding and to synthesize information gained for literature review Chapter 2 of this thesis and for journal articles while prepared for publishing.

A.2 CO_2 neutrality overview

Table A.2-1 Summary of findings on biomass CO_2 neutrality based on the reviewed literature.

Biomass utilization stage	Method of estimate	Findings	Reference
Supply chain pathways	LCA for forest and sawmill residues in the form of wood pellets; electricity production	Different drying fuels, storage emission and dry matter losses could result in 73% higher emissions when wood pellets are used instead of coal; emissions during wood fuel storage are particularly significant	Roder et al., 2015
The management options studied included forest fertilization, elongated rotation periods, varying the type of forest residues extracted, and leaving high stumps.	Simulation-modeling and calculating costs for different scenarios	The sooner carbon neutrality is required, the greater are the costs. The smallest carbon loss occurred when only quickly decomposing branches were collected, whereas the largest carbon loss resulted from harvesting all the residues	Repo et al., 2015
Supply chain pathways	LCA for domestic heating; 3 pathways of forest residues (loose residues, district heating utilizing chips and pellets in domestic stoves)	Supply chain GHG reduction could be beneficial in case of biomass except for the long-term slow decaying biomass – an important factor is biomass feedstock choices	Giuntoli, 2015
Woody biomass a land-based option for fuel poverty reduction -estimates the availability of wood to produce wood fuel in the region and identifies the barriers to the expansion of the wood fuel market for space and water heating purposes.	Scenarios: 1) no existing/ projected houses would adopt wood fuel; 2) new and existing houses go off the gas grid to adopt wood fuel systems; 3) existing houses off the gas grid and 15% of the new houses to adopt wood fuel.	Carbon dioxide emissions reduction from the adoption of wood fuel systems would be significant compared to non-adoption Some of the barriers for the adoption of wood pellet boilers could possibly be mitigated if some additional thought and finance are made available.	Feliciano et al., 2014
Sustainability considerations in the design and planning of forest biomass supply chains for the production of bioenergy and bio products.	A review of literature	The major environmental issues of forest biomass utilization are related to a) carbon balance and GHG emissions, b) PM emissions, and c) the forest ecosystem health. Carbon neutrality will be achieved in the long term, when the new tree generation has reached a harvestable size	Cambero and Sowlati, 2014
DH system, an annual load, annual variable heat-generating costs and technical parameters	Case study – Stockholm DH system; investment optimization software	It is a complex issue to allocate the emissions from alternative DH options, however: 1)investing in new production, energy efficiency/conservation, only direct or local emissions should be	Levihn, 2014

Biomass utilization stage	Method of estimate	Findings	Reference
		accounted for internally; 2)important to understand changed consumption and production and in addition to the marginal perspective in carbon footprint calculations, LCA should be considered	
Supply chain pathways and different conversion methods	LCA of comminuted forest biomass	Most supply-chain GHG emissions arise from soil carbon stocks changes and possible emissions from storage of biomass	Jäppinen, 2014
Supply chain pathways and comparison to reference fossil fuels	LCA, Case study, wood pellet production for electricity, domestic use and export	The forest carbon accounting methods important, cumulative GHG reduction over longer periods (41MtCO_{2eq})	McKechnie, 2014
Harvest-residue-based bioenergy	A synthesis paper	Forest bioenergy is not carbon neutral if forest carbon stocks or sinks are reduced. The intensified removals of the logging residues would decrease the annual carbon sink of these forest soils by 3.1 million tons of CO_{2eq}. Net reductions in the emissions will be achieved only in a longer term.	Vanhala, 2013
Biomass harvesting stage	Adjustments to the previous studies	Carbon capturing continues with mature stands not being harvested which should be accounted for	Holtsmark, 2013
The assessment of the climate impacts from biogenic CO_2 fluxes from single stand to landscape level; the resulting effects on atmospheric CO_2 concentration.	A case study – harvest practice which utilizes collection of wood logs with forest residues left on site	The change in atmospheric CO_2 concentration as a result of biogenic CO_2 from regenerative biomass is reversible; at the landscape level similar increase and impacts from biomass CO_2 like from fossil fuels for the first decades but later, CO_2 from bioenergy stabilizes.	Cherubini et al., 2013
Supply chain comparison	LCA, carbon footprint modeling	Forest type significant factor in carbon footprint which will vary depending on the harvesting scenarios	Newell, 2012
Errors in GHG accounting; recommendations for policy makers	A viewpoint article discusses the scientific background of an Opinion on bioenergy by the Scientific Committee of the European Environment Agency (EEA).	*Baseline error* caused by assuming carbon neutrality on the basis of returned carbon to the atmosphere during the biomass burning; missed C absorptions should the plants had not been harvested; Policies should encourage bioenergy use from biomass that reduces GHG emissions, biomass by-products, wastes, residues without displacing other ecosystems services.	Haberl et al., 2012
Electricity production from biomass (combustion) of residues and dedicated energy crops	Assessment based on: price, efficiency, GHG emissions, availability, limitations, land use, water use and social impacts	The type and growing location of the biomass source determine its sustainability; Electricity generation produces low net carbon emissions, mostly in the form of CO_2,	Evans et al., 2010

Biomass utilization stage	Method of estimate	Findings	Reference
Overview of ongoing initiatives in biomass and bioenergy certification until 2009; the differences and similarities between these initiatives.	A review of literature	Certification may influence direct, local impacts with respect to environmental and social effects of direct bioenergy production; variation in methodologies and default values for calculating GHG balance and carbon sinks exists	van Dam et al., 2010
Full fuel cycle	Case study, modeling	Major factor in evaluation: forest growth rate, conversion efficiency, fossil fuel energy system replaced	Schlamadinger et al.,1996a
Net flux of C to the atmosphere through 4 mechanisms including storage of C in the biosphere and the use of biofuels to displace fossil-fuel use	Mathematical model GORCAM; 16 scenarios	Longer time periods and higher efficiency of replacement of fossil fuels by biofuels favor using trees for bioenergy than for C sequestration	Schlamadinger et al., 1996b
Carbon storage in 3 soil carbon pools and carbon fluxes from these pools	Model development	The time dependent "Carbon Neutrality" (CN) is the ratio of net emission reduction to the "saved" carbon emissions from the substituted energy system; for bioenergy (from logging residues), CN starts as very low at the beginning (eg. between 0.49 and 0.82 after 20 years) and approaches one at infinity.	Schlamadinger et al., 1995

Appendix B UBC Fuel characteristics and consumption, and energy calculations

B.1 Conversion of units used in fuel calculations

1	BTU =	1055 J
1	pound =	0.45359237 kg
1	foot =	0.3048 m

SCF - A standard cubic foot for measuring natural gas is defined as: The amount of natural gas contained at standard temperature and pressure, 60 [ºF] equal to 15 [ºC] and 14.73 [psi] equal to 101.325 [kPa]. In industry, the amount of natural is usually expressed as KSCF (10^3 SCF) or MMSCF (10^6 SCF)

1	ton =	200 lbs = 0.9072 tonnes
1	tonne [t] =	1,000 kg

<u>Heat content of fuels and steam:</u>

Natural gas	heat content/SCF	1050 BTU = 1.107 MJ or 1.107 GJ/KSCF
Fossil fuel oil	heat content/kg	46 MJ/kg
Wood chips (BRDF)	heat content/kg	19.3 MJ as measured (average) at BRDF
	(dry wood)	equals to 19.3 GJ/t
	(at 35% moisture content, wet basis = 54% moisture content, dry basis)	
Steam @165psi	heat content/lb	1197 BTU = 1.2628 MJ or 1.2628 GJ/KLBS

B.2 Fuel consumption and steam produced

Daily data for natural gas and oil consumption and steam produced were summarized by month as presented here, and day/night periods to enable detailed estimates of emissions used later in modeling scenarios as presented in Appendix C.

Table B.2-1 Natural gas and oil consumption (energy input) and steam produced (energy output) at PH and BRDF.

Year 2009 - 2010 PH

Month	Steam from PH [KLBS]	Steam to campus [GJ]	NATURAL GAS [GJ]	Heating OIL [GJ]	Thermal Efficiency [%]
June	34,366	43,399	43,895	0	99
July	32,653	41,236	45,305	0	91
August	30,559	38,591	40,856	0	94
September	36,581	46,195	49,010	0	94
October	57,833	73,033	78,783	0	92
November	73,514	92,836	82,292	18,112	92
December	99,985	126,264	131,739	2,440	94
January	77,225	97,523	100,910	0	96
February	68,670	86,719	89,743	0	96
March	74,719	94,358	97,847	0	96
April	63,936	80,741	83,831	0	96
May	49,822	62,917	65,449	0	96
TOTAL	**699,864**	**883,813**	**909,659**	**20,552**	
				Aver. eff	95%

930 TJ
Energy input NG +oil

Energy output= 699,864 KLBS steam x 0.0012628 TJ/KLBS
equals to **884 TJ of total energy output**

Year 2012 - 2013 PH (and BRDF operational*)

Month	Steam from PH [KLBS]	Steam to campus [GJ]	NATURAL GAS [GJ]	Heating OIL [GJ]	Thermal Efficiency [%]
June	39,867	50,345	55,014	0	91
July	28,257	35,684	37,904	0	94
August	20,957	26,465	37,309	0	71
September	31,197	39,397	42,279	0	93
October	52,604	66,430	73,267	0	90
November	69,456	87,712	94,428	0	93
December	88,120	111,281	119,793	13,694	83
January	92,282	116,537	125,758	0	92
February	75,172	94,930	103,429	0	92
March	69,305	87,521	96,134	0	91
April	51,470	64,999	72,090	0	90
May	32,993	41,665	47,231	0	88
TOTAL	**651,681**	**822,965**	**904,637**	**13,694**	
				Aver. eff	89%

918 TJ
Energy input NG +oil

Energy output= 651,681 KLBS steam x 0.0012628 IJ/KLBS = **823 TJ**
plus from BRDF* 148,920 KLBS steam x 0.0012628 TJ/KLBS = **188 TJ**
equals to **1,011 TJ of total energy output**

Energy input needed if wood completely replaced fossil fuel assuming the same energy output of 1,011 TJ considering efficiency of wood conversion of 68% and moisture content 54% dry basis as reported by BRDF measurements

To calculate energy from wood needed to produce the same amount of steam:

$$\text{Energy from wood [GJ]} = \text{Steam demand [KLBS]}/68 \cdot 100$$

and to calculate the mass of wood with 54% MC_D needed to produce the required energy:

$$\text{wood needed [t]} = \{\text{wood energy needed [GJ]} / 19.3 \text{ GJ/t}\} \cdot 1.54$$

Table B.2-2 Wood requirements for 1,011TJ energy output.

Year 2012 - 2013 PH (and BRDF operational*)				
Month	**Steam from PH [KLBS]**	**Energy from PH steam [GJ]**	**from wood @68%eff [GJ]**	**Wood @ 54% MC_D [t]**
June	39,867	50,345	74,037	5,908
July	28,257	35,684	52,477	4,187
August	20,957	26,465	38,920	3,106
September	31,197	39,397	57,937	4,623
October	52,604	66,430	97,691	7,795
November	69,456	87,712	128,988	10,292
December	88,120	111,281	163,648	13,058
January	92,282	116,537	171,378	13,675
February	75,172	94,930	139,602	11,139
March	69,305	87,521	128,707	10,270
April	51,470	64,999	95,586	7,627
May	32,993	41,665	61,272	4,889
	TOTAL =		1,210,243	**96,569**
plus from BRDF* =			219,000	**17,475**
			TOTAL wood needed =	**114,043**

Based on seasonal and diurnal ratios for steam obtained for 2010-2013 from both plants (PH and BRDF):

2012/13 steam generation =	651,681	[KLBS] at PH	7.80062E+11	[BTU]	=	822,965.18	[GJ] from PH
	148,920	[KLBS] at BRDF	1.78257E+11	[BTU]	=	188,061.39	GJ] from [BRDF
TOTAL=	800,601	KLBS =	9.58319E+11	[BTU]	=	1,011,026.96	[GJ]
					is	1,011.03	TJ
						output energy = energy demand	

Table B.2-3 Seasonal distribution of energy demand of 1,011 TJ for 2012-2013.

Parameter	**DAYTIME [DT]**	**NIGHTTIME [NT]**	**Season total**	**ratio DT/NT**	**ratio season/year**
Units	[TJ]	[TJ]	[TJ]		[%]
summer 2012	78	74	151.7	1.06	15
fall 2012	125	107	232.5	1.16	23
winter 2012/13	223	172	394.3	1.29	39
spring 2013	125	107	232.5	1.16	23
		year total=	**1,011**	**TJ**	

Appendix C Emission estimates used in modeling scenarios

SCENARIO 1: Base case as of 2012-2013, both PH and BRDF were operational, total energy produced 1,011 TJ

[188,061.39 GJ of energy was produced by BRDF and 822,965.18 GJ by PH]

Energy input = 1,194,802 GJ = 1,195 TJ (918,332 GJ from NG and oil and 276,560 GJ from biomass)

Table C-1 Scenario 1 Base case: Daytime and nighttime pollutant emissions from PH per month 2012-2013.

	PM DAY [g]	PM NIGHT [g]	CO DAY [g]	CO NIGHT [g]	CH4 DAY [g]	CH4 NIGHT [g]	NO_2 DAY [g]	NO_2 NIGHT [g]
Jun	21,415	21,296	946,248	940,991	25,923	25,779	1,126,338	1,120,080
July	14,754	14,675	651,946	648,440	17,861	17,765	776,024	771,851
Aug	14,523	14,445	641,722	638,272	17,581	17,486	763,855	759,748
Sep	16,458	16,366	727,202	723,162	19,922	19,812	865,603	860,794
Oct	28,520	28,367	1,260,196	1,253,421	34,524	34,339	1,500,037	1,491,972
Nov	36,757	36,553	1,624,170	1,615,147	44,496	44,248	1,933,282	1,922,541
Dec	88,673	88,196	2,165,545	2,153,902	60,967	60,639	2,662,861	2,648,544
Jan	48,952	48,689	2,163,031	2,151,402	59,258	58,940	2,574,698	2,560,856
Feb	40,261	40,021	1,778,981	1,768,392	48,737	48,447	2,117,556	2,104,951
Mar	37,421	37,220	1,653,508	1,644,618	45,299	45,056	1,968,203	1,957,621
Apr	28,062	27,906	1,239,943	1,233,054	33,969	33,781	1,475,928	1,467,729
May	18,385	18,286	812,373	808,005	22,256	22,136	966,984	961,785

Table C-2 Scenario 1 Base case: Daytime and nighttime pollutant emissions from BRDF per month 2012-2013.

	PM DAY [g]	**PM NIGHT [g]**	**CO DAY [g]**	**CO NIGHT [g]**	**CH4 DAY [g]**	**CH4 NIGHT [g]**	**NO_2 DAY [g]**	**NO_2 NIGHT [g]**
Jun	4,609	4,584	168,241	167,306	104,056	103,478	842,357	837,677
July	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Aug	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Sep	4,609	4,584	168,241	167,306	104,056	103,478	842,357	837,677
Oct	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Nov	4,609	4,584	168,241	167,306	104,056	103,478	842,357	837,677
Dec	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Jan	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Feb	4,609	4,582	168,241	167,239	104,056	103,436	842,357	837,342
Mar	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828
Apr	4,609	4,584	168,241	167,306	104,056	103,478	842,357	837,677
May	4,609	4,585	168,241	167,336	104,056	103,496	842,357	837,828

Table C-3 Scenario 1 Base case: Resulting emissions daytime and nighttime pollutant emissions from PH and BRDF per month 2012-2013.

Period	PM DAY [g]	PM NIGHT [g]	CO DAY [g]	CO NIGHT [g]	CH_4 DAY [g]	CH_4 NIGHT [g]	NO_2 DAY [g]	NO_2 NIGHT [g]
Jun	26,024	25,880	1,114,489	1,108,297	129,979	129,257	1,968,694	1,957,757
July	19,364	19,260	820,186	815,777	121,916	121,261	1,618,380	1,609,679
Aug	19,132	19,030	809,963	805,609	121,636	120,982	1,606,211	1,597,576
Sep	21,067	20,950	895,443	890,468	123,978	123,289	1,707,960	1,698,471
Oct	33,129	32,951	1,428,437	1,420,758	138,580	137,835	2,342,393	2,329,800
Nov	41,367	41,137	1,792,411	1,782,453	148,551	147,726	2,775,638	2,760,218
Dec	93,282	92,781	2,333,786	2,321,238	165,023	164,135	3,505,217	3,486,372
Jan	53,562	53,274	2,331,272	2,318,738	163,314	162,436	3,417,055	3,398,684
Feb	44,870	44,603	1,947,222	1,935,631	152,793	151,883	2,959,912	2,942,294
Mar	42,031	41,805	1,821,749	1,811,954	149,355	148,552	2,810,560	2,795,449
Apr	32,671	32,489	1,408,184	1,400,360	138,025	137,258	2,318,285	2,305,406
May	22,994	22,871	980,614	975,342	126,312	125,632	1,809,340	1,799,612

<u>SCENARIO 2 and 4:</u> Case when PH would be operational only, total energy produced 1,011 TJ

Energy input = 1,133,232 GJ =1,133 TJ

Table C-4 Scenario 2: Daytime and nighttime pollutant emissions per month 2012-2013 if only PH is operational.

Period	PM DAY [g]	PM NIGHT [g]	CO DAY [g]	CO NIGHT [g]	CH_4 DAY [g]	CH_4 NIGHT [g]	NO_2 DAY [g]	NO_2 NIGHT [g]
Jun	28,422	28,264	1,255,848	1,248,871	34,405	34,214	1,494,861	1,486,556
July	21,742	21,625	960,686	955,521	26,319	26,177	1,143,523	1,137,375
Aug	21,510	21,395	950,462	945,352	26,039	25,899	1,131,354	1,125,272
Sep	23,464	23,334	1,036,802	1,031,042	28,404	28,246	1,234,126	1,227,270
Oct	35,527	35,336	1,569,796	1,561,357	43,006	42,775	1,868,560	1,858,514
Nov	43,764	43,521	1,933,770	1,923,027	52,977	52,683	2,301,805	2,289,017
Dec	58,968	58,651	2,605,585	2,591,576	71,382	70,999	3,101,479	3,084,804
Jan	55,959	55,658	2,472,631	2,459,337	67,740	67,376	2,943,221	2,927,398
Feb	46,878	46,599	2,071,381	2,059,051	56,747	56,410	2,465,605	2,450,929
Mar	44,428	44,189	1,963,108	1,952,554	53,781	53,492	2,336,726	2,324,163
Apr	35,068	34,873	1,549,543	1,540,934	42,451	42,215	1,844,451	1,834,205
May	25,392	25,255	1,121,973	1,115,941	30,737	30,572	1,335,507	1,328,326

<u>SCENARIO 3:</u> Fossil fuels are completely replaced with wood, BRDF would be operational only, total energy produced 1,011 TJ

Energy input = 1,486,803.20 GJ = 1,487 TJ

Table C-5 Scenario 3 Daytime and nighttime pollutant emissions per month 2012-2013 if only BRDF is operational.

Period	PM DAY [g]	PM NIGHT [g]	CO DAY [g]	CO NIGHT [g]	CH_4 DAY [g]	CH_4 NIGHT [g]	NO_2 DAY [g]	NO_2 NIGHT [g]
Jun	19,417	19,309	708,713	704,775	438,334	435,899	3,548,418	3,528,705
July	15,105	15,023	551,320	548,356	340,988	339,155	2,760,377	2,745,536
Aug	12,393	12,327	452,355	449,923	279,778	278,274	2,264,872	2,252,695
Sep	16,197	16,107	591,180	587,896	365,641	363,609	2,959,950	2,943,505
Oct	24,148	24,018	881,385	876,646	545,130	542,200	4,412,960	4,389,234
Nov	30,407	30,238	1,109,851	1,103,685	686,435	682,622	5,556,857	5,525,986
Dec	37,339	37,138	1,362,872	1,355,544	842,927	838,395	6,823,692	6,787,006
Jan	38,885	38,676	1,419,301	1,411,670	877,828	873,108	7,106,227	7,068,021
Feb	32,530	32,336	1,187,337	1,180,270	734,360	729,989	5,944,819	5,909,433
Mar	30,351	30,188	1,107,803	1,101,847	685,168	681,485	5,546,602	5,516,781
Apr	23,727	23,595	866,019	861,208	535,627	532,651	4,336,026	4,311,937
May	16,864	16,773	615,528	612,219	380,700	378,653	3,081,857	3,065,288

SCENARIO 5: Case when only PH would be operational, total energy produced 884 TJ as in 2009-2010.

Energy input = 930,211.17 GJ = 930 TJ

Table C-6 Scenario 5 Daytime and nighttime pollutant emissions per month 2009-2010 when only PH was operational.

Period	PM DAY [g]	PM NIGHT [g]	CO DAY [g]	CO NIGHT [g]	CH_4 DAY [g]	CH_4 NIGHT [g]	NO_2 DAY [g]	NO_2 NIGHT [g]
Jun	17,087	16,992	754,992	750,798	20,684	20,569	898,682	893,689
July	17,635	17,541	779,243	775,054	21,348	21,233	927,549	922,562
Aug	15,904	15,818	702,729	698,951	19,252	19,148	836,472	831,975
Sep	19,078	18,972	842,974	838,291	23,094	22,966	1,003,409	997,834
Oct	30,667	30,502	1,355,075	1,347,790	37,124	36,924	1,612,973	1,604,301
Nov	87,637	87,150	1,554,431	1,545,796	44,754	44,505	1,962,914	1,952,009
Dec	58,772	58,456	2,284,643	2,272,360	62,882	62,544	2,734,631	2,719,928
Jan	39,280	39,069	1,735,644	1,726,313	47,550	47,294	2,065,972	2,054,864
Feb	34,933	34,725	1,543,571	1,534,383	42,288	42,036	1,837,343	1,826,407
Mar	38,088	37,883	1,682,962	1,673,914	46,106	45,858	2,003,263	1,992,492
Apr	32,632	32,451	1,441,886	1,433,876	39,502	39,282	1,716,306	1,706,771
May	25,477	25,340	1,125,723	1,119,671	30,840	30,674	1,339,970	1,332,766

Appendix D Results of ambient air quality and health risks assessment

Table D-1 Summary of ambient air quality, iF and IS for five district heating operational scenarios at UBC.

Scenario			**Scenario 1: Base case: Biomass and NG/oil**			**Scenario 2: NG only**			**Scenario 3: Biomass only**			**Scenario 4: Biomass and varying population**			**Scenario 5: NG/oil with 2009/10 emissions**		
Period / Parameter *			$PM_{2.5}$	CO	NO_2	$PM_{2.5}$	CO	NO_2	$PM_{2.5}$	CO	NO_2	$PM_{2.5}$	CO	NO_2	$PM_{2.5}$	CO	NO_2
SUMMER	DAYtime	Mean [$\mu g/m^3$]	0.012	0.499	0.892	0.014	0.607	0.723	0.008	0.299	1.495	0.008	0.299	1.495	0.011	0.471	0.561
		Max [$\mu g/m^3$]	1.74	76.88	91.52	2.31	102.04	121.45	1.03	37.46	187.59	1.03	37.46	187.59	1.40	61.73	73.47
		∑iF (ppm)	26.35	26.76	23.00	29.74	29.74	29.74	18.20	18.20	18.20	8.62	8.62	8.62	32.74	32.74	32.74
	NIGHTtime	Mean [$\mu g/m^3$]	0.007	0.302	0.480	0.009	0.390	0.464	0.003	0.118	0.593	0.003	0.118	0.593	0.007	0.301	0.359
		Max [$\mu g/m^3$]	0.46	20.18	29.51	0.61	26.79	31.89	0.65	23.80	119.17	0.65	23.80	119.17	0.43	19.04	22.67
		∑iF (ppm)	1.36	1.34	1.55	1.24	1.24	1.24	2.10	2.10	2.10	0.61	0.61	0.61	1.35	1.35	1.35
FALL	DAYtime	Mean [$\mu g/m^3$]	0.012	0.536	0.836	0.015	0.640	0.761	0.008	0.289	1.449	0.008	0.289	1.449	0.017	0.529	0.640
		Max [$\mu g/m^3$]	2.09	92.46	110.06	2.60	115.18	137.10	2.05	74.65	**373.73**	2.05	74.65	373.73	3.65	99.43	118.34
		∑iF (ppm)	20.44	20.76	17.43	23.48	23.48	23.48	12.14	12.14	12.14	12.14	12.14	12.14	23.48	23.48	23.48
	NIGHTtime	Mean [$\mu g/m^3$]	0.006	0.257	0.384	0.007	0.310	0.369	0.003	0.112	0.563	0.003	0.112	0.563	0.009	0.255	0.311
		Max [$\mu g/m^3$]	1.79	79.20	97.41	2.23	98.66	117.44	1.42	51.84	**259.58**	1.42	51.84	259.58	1.93	85.17	101.37
		∑iF (ppm)	0.77	0.78	0.74	0.81	0.81	0.81	0.77	0.77	0.77	0.77	0.77	0.77	0.81	0.81	0.81
WINTER	DAYtime	Mean [$\mu g/m^3$]	0.022	0.776	1.156	0.019	0.838	0.998	0.013	0.456	2.284	0.013	0.456	2.284	0.015	0.645	0.769
		Max [$\mu g/m^3$]	2.28	82.89	101.11	2.13	94.02	111.91	2.39	87.25	**436.87**	2.39	87.25	436.87	1.50	65.99	78.56
		∑iF (ppm)	15.76	15.75	15.32	15.93	15.93	15.93	13.55	13.55	13.55	13.55	13.55	13.55	15.93	15.93	15.93
	NIGHTtime	Mean [$\mu g/m^3$]	0.012	0.413	0.577	0.011	0.312	0.371	0.005	0.167	0.834	0.005	0.167	0.834	0.008	0.351	0.419
		Max [$\mu g/m^3$]	3.19	82.38	98.10	2.13	94.15	112.07	1.48	53.93	**270.03**	1.48	53.93	270.03	2.12	82.23	98.43
		∑iF (ppm)	0.66	0.65	0.66	0.44	0.44	0.44	0.67	0.67	0.67	0.67	0.67	0.67	0.65	0.65	0.65
SPRING	DAYtime	Mean [$\mu g/m^3$]	0.018	0.767	1.294	0.020	0.881	1.048	0.012	0.449	2.247	0.012	0.449	2.247	0.018	0.807	0.961
		Max [$\mu g/m^3$]	1.55	62.56	81.84	1.85	81.00	97.16	1.14	41.67	**208.63**	1.14	41.67	208.63	1.73	76.64	91.23
		∑iF (ppm)	29.96	29.37	27.93	31.28	31.28	31.28	21.43	21.43	21.43	21.43	21.43	21.43	31.29	31.29	31.29
	NIGHTtime	Mean [$\mu g/m^3$]	0.009	0.382	0.607	0.010	0.451	0.537	0.005	0.172	0.859	0.005	0.172	0.859	0.009	0.415	0.495
		Max [$\mu g/m^3$]	1.33	53.44	69.91	1.58	69.72	83.00	1.50	54.88	**274.77**	1.50	54.88	274.77	1.35	59.77	71.15
		∑iF (ppm)	1.02	0.99	1.10	0.97	0.97	0.97	1.28	1.28	1.28	1.28	1.28	1.28	0.97	0.97	0.97
$\sum iF_{annual}$ [ppm]			96.32	96.40	87.73	103.89	103.89	103.89	70.14	70.14	70.14	59.07	59.07	59.07	107.22	107.22	107.22
E [DALY/kg]			0.0007	7.31E-07	8.91E-05	0.0007	7.31E-07	8.91E-05	0.0007	7.31E-07	0.0000891	0.0007	7.31E-07	0.0000891	0.0007	7.3E-07	8.91E-05
m [kg]			897	35,270	57,521	880	38,876	46,275	593	21,648	108,387	593	21,648	108,387	832	31,521	37,775
$\sum IS_{annual}$ [DALY]**			**60**	**2**	**450**	**64**	**3**	**428**	**29**	**1**	**677**	**25**	**1**	**570**	**62**	**2**	**361**
$\sum IS_{scenario}$ [DALY			**513**			**495**			**708**			**596**			**426**		

*1-hour averaging period **iF expressed in *per million* , ppm
Exceedances of Air Quality Objectives presented in bold

Appendix E Global impacts data

E.1 Emission factors for energy products

Table E.1-1 Emission factors for natural gas.

Pollutant	Upstream [kg/MJ]	Combustion [kg/MJ]	TOTAL [kg/MJ]
CO_2 fossil	8.41E-03	4.92E-02	5.76E-02
CO_2 biogenic	7.98E-05	-	7.98E-05
CH_4	1.60E-04	9.42E-07	1.61E-04
CH_4 biogenic	-	-	-
N_2O	2.15E-07	9.02E-07	1.12E-06
NO_x as NO_2	4.55E-05	4.01E-05	8.65E-05
SO_x	1.03E-05	2.58E-07	1.05E-05
PM	5.96E-07	7.79E-07	1.38E-06
CO	6.60E-06	3.44E-05	4.10E-05
CO biogenic	-	-	-
NMVOC	3.46E-06	2.25E-06	5.72E-06

Table E.1-2 Emission factors for heavy fuel oil.

Pollutant	**Upstream [kg/MJ]**	**Combustion [kg/MJ]**	**TOTAL [kg/MJ]**
CO_2 fossil	1.13E-02	6.85E-02	7.98E-02
CO_2 biogenic	4.75E-04	-	4.75E-04
CH_4	1.43E-04	6.60E-07	1.44E-04
CH_4 biogenic	-	-	-
N_2O	3.67E-07	8.0E-07	1.17E-06
NO_x	4.17E-05	3.71E-05	7.24E-05
SO_x	3.34E-05	4.56E-05	4.89E-04
PM	1.99E-06	6.14E-06	8.13E-06
CO	1.09E-05	1.54E-05	2.63E-05
CO biogenic	-	-	-
NMVOC	3.99E-06	1.04E-06	5.03E-06

Table E.1-3 Emission factors for middle distillates.

Pollutant	Upstream [kg/MJ]	Combustion* [kg/MJ]	TOTAL [kg/MJ]
CO_2 fossil	1.82E-02	7.05E-02	8.88E-02
CO_2 biogenic	6.20E-04		6.20E-04
CH_4	1.57E-04	1.6E-07	1.57E-04
CH_4 biogenic	-	-	-
N_2O	1.0E-06	2.86E-05	2.93E-05
NO_x	5.50E-05	4.0E-05	9.45E-05
SO_x	6.80E-05	6.54E-07	6.84E-05
PM	5.50E-06	3.8E-06	8.55E-06
CO	1.80E-05	2.15E-05	3.90E-05
CO biogenic	-	-	-
NMVOC	4.91E-06	-	4.91E-06

*GHGenius based on AP-42 emission factors.

Table E.1-4 Emission factors for middle distillates for HDV operation.

Pollutant	Upstream [kg/tkm]	Vehicle operation [kg/tkm]	TOTAL [kg/tkm]*
CO_2 fossil	3.76E-02	1.43E-01	1.81E-01
CO_2 biogenic	1.33E-06	-	1.33E-06
CH_4	3.25E-04	8.87E-06	3.34E-04
CH_4 biogenic	-	-	-
N_2O	1.44E-06	6.17E-06	7.61E-06
NO_x	1.13E-04	5.39E-05	1.66E-04
SO_x	1.40E-04	5.35E-06	1.45E-04
PM	9.81E-06	2.64E-06	1.24E-05
CO	3.62E-05	2.47E-05	6.09E-05
CO biogenic	-	-	-
NMVOC	1.01E-05	1.49E-05	2.50E-05

The totals were calculated before rounding upstream and vehicle operation emissions.

E.2 Annual emissions over life cycle stages

Table E.2-1 Annual emission by process and transport stages for Scenario 1: NG, fuel oil and biomass.

Pollutant	NG upstream [kg/yr]	Oil upstream [kg/yr]	NG combustion [kg/yr]	Oil combustion [kg/yr]	Wood transport* [kg/yr]	Wood processing Cloverdale [kg/yr]	Wood gasification [kg/yr]	TOTAL [kg/yr]
CO_2 fossil	7.61E+06	1.55E+05	4.45E+07	9.38E+05	1.32E+05	8.93E+03	-	5.33E+07
CO_2 bio.	7.22E+04	6.50E+03	-	-	9.75E-01	4.33E+03	2.54E+07	2.54E+07
CH_4	1.45E+05	1.96E+03	8.53E+02	9.04E+00	2.44E+02	7.50E+01	2.50E+03	1.48E+05
N_2O	1.94E+02	5.03E+00	8.16E+02	1.10E+01	5.58E+00	3.75E-01	1.55E+03	2.58E+03
NO_x (NO_2)	4.12E+04	5.71E+02	3.70E+04	4.21E+02	1.22E+02	2.19E+01	2.02E+04	9.96E+04
SO_x	9.32E+03	4.57E+02	0.00E+00	6.24E+03	1.06E+02	1.80E+01	-	1.61E+04
PM	5.39E+02	2.73E+01	7.04E+02	8.41E+01	9.12E+00	4.69E+01	1.11E+02**	1.25E+04
CO	5.97E+03	1.49E+02	3.11E+04	2.10E+02	4.47E+01	3.75E+04	4.04E+03	3.75E+04
NMVOC	3.13E+03	5.46E+01	2.04E+03	1.42E+01	1.83E+01	1.81E+00	1.19E+03	6.45E+03
CO_2 eq [kg/year]	1.17E+07	2.11E+05	4.48E+07	9.42E+05	1.41E+05	1.12E+04	4.88E+05	5.83 E+07 (CO_{2eq})

*Includes both transportation segments – from industry to Cloverdale and from Cloverdale to UBC.
** ESP in place.

Table E.2-2 Annual emission by process for Scenario 2: Natural gas only.

Pollutant	**NG upstream [kg/yr]**	**NG combustion [kg/yr]**	**TOTAL [kg/yr]**
CO_2 fossil	9.53E+06	5.57E+07	6.53E+07
CO_2 biogenic	9.04E+04	-	9.04E+04
CH_4	1.81E+05	1.07E+03	1.82E+05
N_2O	2.44E+02	1.02E+03	1.27E+03
NO_x (NO_2)	5.16E+04	4.64E+04	9.80E+04
SO_x	1.17E+04	0.00E+00	1.17E+04
PM	6.75E+02	8.82E+02	1.56E+03
CO	7.48E+03	3.90E+04	4.65E+04
NMVOC	3.92E+03	2.55E+03	6.47E+03
CO_2 eq [kg/year]	1.47E+07	5.61E+07	7.08E+07 (CO_{2eq})

Table E.2-3 Annual emission by process and transport stages for Scenario 3: Biomass only.

Pollutant	**Wood transport* [kg/yr]**	**Wood processing Cloverdale [kg/yr]**	**Wood gasification [kg/yr]**	**TOTAL [kg/yr]**
CO_2 fossil	1.05E+06	5.36E+04	0.00E+00	1.11E+06
CO_2 bio.	7.76E+00	2.60E+04	1.36E+08	1.36E+08
CH_4	1.95E+03	4.49E+02	1.34E+04	1.58E+04
N_2O	4.44E+01	2.25E+00	8.31E+03	8.36E+03
NO_x (NO_2)	9.71E+02	1.31E+02	1.09E+05	1.10E+05
SO_x	8.47E+02	1.08E+02	0.00E+00	9.55E+02
PM	7.26E+01	2.81E+02	5.93E+02**	9.47E+02
CO	3.56E+02	4.62E+01	2.17E+04	2.21E+04
NMVOC	1.46E+02	1.09E+01	6.39E+03	6.55E+03
CO_2 eq [kg/year]	1.12E+06	6.69E+04	2.62E+06	3.81E+06 (CO_{2eq})

*Includes both transportation segments – from industry to Cloverdale and from Cloverdale to UBC.
** ESP in place.

Table E.2-4 Annual emission by process and transport stages for Scenario 3: Biomass only, changed transportation distance.

Pollutant	**Wood transport* [kg/yr]**	**Wood processing Cloverdale [kg/yr]**	**Wood gasification [kg/yr]**	**TOTAL [kg/yr]**
CO_2 fossil	2.01E+06	5.36E+04	-	2.06E+06
CO_2 bio.	1.48E+01	2.60E+04	1.36E+08	1.36E+08
CH_4	3.70E+03	4.49E+02	1.34E+04	1.76E+04
N_2O	8.46E+01	2.25E+00	8.31E+03	8.40E+03
NO_x (NO_2)	1.85E+03	1.31E+02	1.09E+05	1.11E+05
SO_x	1.61E+03	1.08E+02	0.00E+00	1.72E+03
PM	1.38E+02	2.81E+02	5.93E+02**	1.01E+03
CO	6.77E+02	2.33E+03	2.17E+04	2.25E+04
NMVOC	2.78E+02	1.09E+01	6.39E+03	6.68E+03
CO_2 eq [kg/year]	2.13E+06	6.69E+04	2.628E+06	4.83E+06 (CO_{2eq})

*Includes both transportation segments – from industry to Cloverdale and from Cloverdale to UBC.
** ESP in place.

Appendix F Meeting CAP2020 GHG reduction goals

According to the latest UBC report (Wauthy and Giffin, 2017), two energy supply options are being considered for reaching the University's Climate Action Plan (CAP) for GHG reductions goals of 67% below 2007 level by 2020:

- Displacement of natural gas with carbon neutral Renewable Natural Gas (RNG) at the newly constructed and operational CEC (Campus Energy Centre), and
- Expansion of the existing BRDF with an addition of a biomass boiler.

The second option, an expansion of the existing BRDF, is discussed here. It should be noted that the intention of this discussion is not to provide a detailed economic analysis which is beyond the scope of this study, but rather to reveal some economic aspects of this possibly future option.

The new ADES (Academic District Energy System) center at UBC which included CEC (Campus Energy Centre) costed $88.3 M (UBC, 2013) and was designed with natural gas as the fuel. With respect to fuel choices as previously discussed BRDF which utilizes biomass is a good contribution to GHG reduction. However, costs associated with its construction and maintenance could pose obstacles for its adoption. In order to meet heating demand target of 1011 TJ used in this study, capital cost of BRDF expansion is calculated using a cost scaling factor of 0.6 based on the ratio of plant's potential and current output as per the following equation:

Capital investment for the new plant = (7-1)
= (Total energy demand / Current BRDF heat output capacity)^$^{0.6}$ x initial capital investment for BRDF

Where: total energy demand is 1,011 TJ, BRDF heat output as of 2012-2013 is 188 TJ and capital investment for the heating portion of plant of $19.2 M. The investment for an expanded BRDF in order to meet the UBC campus heating demand is thus estimated to be $52.7 M.

It is assumed that biomass would be mostly sourced locally as it is at present, since supply analysis indicated a large surplus of solid wood waste in the region at a pretty stable cost compared to other commodities (Wauthy and Giffin, 2017). Here, $79.59/OMDT (a 5-year fixed price of $71/OMDT plus GST and PST) as of 2017 is considered in O&M calculations based on the latest Commodity report (Wauthy and Giffin, 2017). According to this report, biomass prices are expected to remain stable over a period of time due to increased supply forecasts. With a thermal efficiency of 68% (calculated based on 2012-2013 data), 74,054 ODMT of wood is needed to meet energy demand, which would cost $5.9 M annually. Costs of other commodities were not included in this analysis.

Ash disposal ($3.3 K) and plant operation employee salaries ($1.8 M) are estimated arbitrarily[39] using factors of 5.5 and 3, respectively whereas other O&M costs are estimated as earlier stated as 5% of capital investments (equals to $2.6 M). Carbon offset for wood purchased at $\$0.06/GJ_{input}$ would result in an annual carbon cost of $8.9 K. The total annual O&M cost would in such case be $10.5 M and $184 M over the plants' lifetime (20 years). The total PV, which includes both capital and O&M costs for expanded BRDF, is estimated to reach $237 M which indicates increased costs of $28 M compared to option A (PH only) and almost $8 M compared

[39] Estimates based on the expansion factor and assuming the same operating conditions.

to option B (PH and BRDF). It should be noted that those expenditures may be even higher when other costs such as other commodities and their respective carbon taxes, biomass storage and other parameters are included in the economic analysis.

When externalities in case of using biomass to meet the total energy demand for UBC campus are considered, there exist noticeable savings in the total PV of external costs: $18 M compared to option A (natural gas only) and almost $15M compared to option B (combined biomass and natural gas). This is largely due to the avoided costs of CO_2 when biomass is used. However, external costs associated with fine particles increase to $2 M and oxides of nitrogen to $8 M over the plants' lifetime. Figure 6.4 illustrates PV costs of considered pollutants excluding CO_2 for previously discussed options and potential expanded BRDF plant.

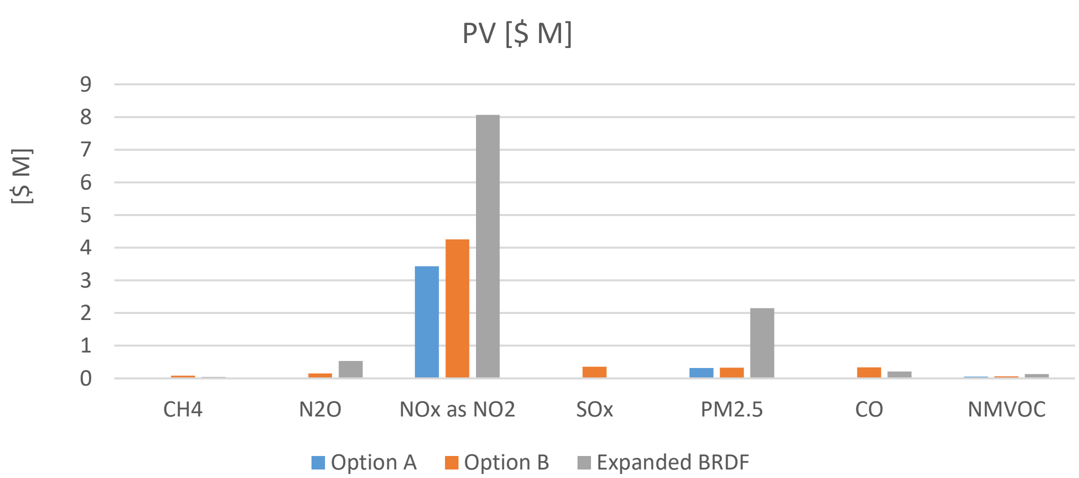

Figure F 1 External costs for option A (natural gas only), option B (natural gas and biomass) and potential BRDF expansion, over plants' lifetime. CO_2 costs are excluded.

Preliminary investigation into possible BRDF expansion indicated that costs calculated as total PV will be higher than options A and B, external costs of NOx and $PM_{2.5}$ over plants' lifetime will increase by $8 M and $2 M respectively whereas savings in carbon tax and offsets will be noticeable at $25 M compared to option A and $20 M compared to option B.