Assessment of Urban Greenhouse Gas Emission Inventory in Montréal

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ABSTRACT

Assessment of Urban Greenhouse Gas Emission Inventory in Montréal

Shadnoush Pashaei Farahani

There is an increasing concern about global warming resulting from greenhouse gas (GHG) emissions. GHGs can be produced from a wide range of anthropogenic activities at different spatial and temporal scales. Since most of the world population lives in cities, emission from urban areas is an important source of GHGs. The city is a complicated system consisting of various components and processes. Efforts have been made to mitigate urban GHG emissions. However, there is a lack of available methods for effective assessment of such emissions. Many urban sources and factors which can influence the emissions are still unknown. In the present study, the contributing factors in an urban area were identified and the GHG emission from municipal activities was assessed. A model for the assessment of urban GHG emissions was developed. Based on the collected data, a case study was conducted to evaluate urban GHG emissions in Montreal. The comprehensive assessment included the emissions from transportation (i.e. public, personal), electricity consumption, natural gas, heating oil, waste disposal, and wastewater treatment as well as the carbon sequestered by green space. This study provided a new approach for the comprehensive evaluation of urban GHG emissions. The results can help better understand the emission process, identify the major emission sources and develop the appropriate strategies for emission reduction.

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LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
CALGAPS	California Greenhouse gas (GHG) Policy evaluation model
COD	Chemical Oxygen Demand
CRD	Construction, Renovation, and Demolition
CTP	Climate Tipping Potential
EDGAR	Emission Database for Global Atmospheric
GEIA	Global Emission Inventory Activity
GHGs	Greenhouse Gases
HHW	Hazardous Household Waste
IGBP	International Geosphere-Biosphere Programme
LCA	Life Cycle Assessment
LPG	Liquefied Petroleum Gas
LULUCF	Land Use, Land-Use Change and Forestry
MBN	Municipal Benchmarking Network
MSW	Municipal Solid Waste
ODC	Ozone-Depleting Chemical
SWD	Solid Waste Disposal
TNO	Netherlands Organisation for Applied Scientific Research
WWTPs	Wastewater Treatment Plants
EP	Per person
LEED	Leadership in Energy and Environmental Design
ITCs	Information Technology and Communication equipment

CHAPTER 1. INTRODUCTION

There is an increasing concern for earth temperature increase caused by anthropogenic perturbation (map, 2019; Samaniego et al., 2018). The rising greenhouse gas (GHG) emission results in the change of radiative pattern in the atmosphere, which would increase the average surface temperature and eventually lead to the changing global climate. GHGs can be produced from a broad range of anthropogenic activities at different spatial and temporal scales(Li et al., 2018). In particular, emission from an urban area is an important source of GHGs. 54% of the global population lived in urban areas in 2014 and by 2050, this ratio will increase to 66% of the global population. About 75% of energy consumption and 80% of GHG emissions globally can be attributed to the urban activities (Hu et al., 2016). Cities may consume a large amount of energy to meet the demands of transport, industrial and commercial, heating and cooling activities. In addition, solid wastes and wastewater are also mostly produced in urban agglomerations (Ebner et al., 2015). Therefore, the efforts of municipalities are crucial for achieving the goal of GHG reduction.

The GHG inventory is a tool to evaluate the status of emissions and the potential for mitigation. The Intergovernmental Panel on Climate Change (IPCC) provides a detailed methodological framework to accomplish the inventories (IPCC, 2006). It assesses the greenhouse gases emitted from main sectors including energy, industrial processes, and product use, agriculture, forestry, and other land use, and waste. These emissions inventories provide a general picture of large-scale patterns of greenhouse gas emissions. The city is a complicated system consisting of various components and processes. Some studies about the GHG emission assessment in urban areas have been reported previously. Qi et al. (2018) investigated the inventory of GHG emission and its environmental and economic impacts on Jinan, using a hybrid life cycle assessment (LCA) method. The economic burden on human health was also compared with that on GHG emission and ecosystem. Gurjar et al. (2004) reported an emission inventory for Delhi, including a range of air pollutants and GHG emissions. Power plants were found to be the main emission source of SO_2 and suspended particles, while the transport sector was the largest source of NOx, CO, and a non-methane volatile organic compound. Hillman and Ramaswami (2010) proposed a hybrid lifecycle-based GHG emission assessment method for cities. The cross-boundary activities were found to be an important contributor to urban GHG emissions. Schmidt

Dubeux and Rovere (2007) studied the GHG emission of Rio de Janeiro and the potential benefits from GHG reduction measures were evaluated. In addition, some municipalities also conducted some general GHG emission assessments (Municipality of Oslo, 2018; Natural Resources Canada, 2018; The City of New York, 2017). There were some GHG emissions inventory assessments for countries and provinces and large cities. However, there is still a lack of available methods for effective assessment of such urban emissions, many urban sources and factors which can influence the emissions are still unknown. Therefore, there is an urgent need to determine the urban GHG sources and evaluate the emission in a comprehensive manner.

In the present study, the GHG emission from municipal activities will be assessed from a new perspective. A generalized model will be developed for the assessment of urban GHG emissions at first. Based on the collected data of Montréal in Canada, a case study will then be conducted to evaluate GHG emissions from transportation (i.e. public and private), electricity consumption, natural gas use, waste disposal, and wastewater treatment. To better understand the emission patterns, the interaction among different factors in the model will be investigated based on the factorial analysis. The results can help better understand the urban GHG emission characteristics and develop the corresponding strategy for GHG reduction.

In the thesis, Chapter 1 is an introduction of this study. Chapter 2 is the literature review including GHG emissions, urban GHG emissions, and methodology of assessment of municipal GHG emissions. Chapter 3 introduces the methodology to assess urban GHG emissions. Chapter 4 shows the results for the methodology applied to Montréal, Canada as a case study. Chapter 5 is the sensitivity analysis and impact of each factor in the assessment. Chapter 6 is the summary of this study and suggestions for future studies.

CHAPTER 2. LITERATURE REVIEW

2.1. General Knowledge of Greenhouse Gas Emissions

There is an increasing concern about the rising temperature of Earth's atmosphere, a phenomenon which has been accompanied by extreme weather such as flooding, drought, and wildfires. The buildup in the atmosphere of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), hydrofluorocarbons (HFCs), nitrogen oxide (N_2O), and sulfur hexafluoride (SF6), has been shown to contribute to the phenomenon of global warming (Tajima et al., 2004). Rising GHG emissions, resulting in changes to radiative patterns in the atmosphere, has, in turn, increased the average surface temperature and eventually lead to the changing global climate. In 2016, total global GHG emissions increased slightly by roughly 0.5% (±1%), to about 49.3 Gt CO_2eq. The year 2016 was a leap year, and therefore 0.3% longer than a non-leap year. In consideration of this, together with the 0.2% increase in 2015, the 2016 emission increase was the slowest annual increase since the early 1990s, not including the global recession years (1975, 1982, 1991 and 2009). This has been the result mainly of lower coal consumption from fuel due to the shift toward natural gas and increased renewable power generation, particularly wind and solar power. CO_2, at approximately 72%, represents the majority of these emissions, while CH_4, N_2O, and fluorinated gases (F-gases) represent 19%, 6%, and 3%, respectively. Due to the uncertainty of emissions from land use, land-use change and forestry (LULUCF) and their large interannual variations, these percentages do not include net emissions from LULUCF, which are usually accounted for separately. They mostly consist of net CO_2 emissions from changes in land use and land cover, plus small amounts in CH_4 and N_2O from forest and peat fires. When including LULUCF emissions for 2016, estimated global total GHG emissions come to 53.4 Gt CO_2-eq.

Non-CO_2 GHG emissions are derived from various sources and are much more uncertain than CO_2 emissions, with the rate of uncertainty at the country or global scale being in the order of 30% or more (by comparison, for CO_2 the rate of uncertainty is closer to 10%). In recent years, non-CO_2 GHG emissions have continued to increase more rapidly than CO_2 emissions, by 1.5% in 2014, 1.2% in 2015 and 1.0% in 2016, with CO_2 emissions over the same period, have risen by a respective 0.8%, −0.2%, and 0.3%. In 2016, CH_4 emissions remained at almost the same level as in 2015, experiencing only 0.3% growth (which can be attributed to 2016 having been a leap year), to a total of 9.2 Gt CO_2-eq. CH_4 accounts for the largest share of non-CO_2 GHG emissions, including predominantly non-dairy cattle, with over 16% of global CH_4 emissions in 2016. In fact, cattle are responsible for 23% of CH_4 emissions worldwide, while 25% of CH_4 emissions are produced by coal mining, oil, and natural gas production and gas distribution, and rice cultivation accounts for 10% of CH_4 emissions. N_2O emissions in 2016 amounted to 2.9 Gt CO_2_eq, and increased by 1.3% in comparison to 2015. The major sources of N_2O emissions are the manure in pastures, rangeland and paddocks, and synthetic fertilizers, which increased by 22% and 18%, respectively, in 2016. Agriculture, including indirect N_2O emissions, accounted for about 75% of N_2O emissions, representing the fastest-growing category over the preceding three years. It is also worth noting, in recent years, savanna fires have been responsible for about 5% of N_2O emissions (Olivier et al., 2017).

Some recent studies have focused on GHG emissions trends in specific areas. Li et al. (2018), for instance, looked at the trends in Japan's GHG emissions and also examined its major contributors. They found that Japan's GHG emissions totaled 1.3 billion CO_2_eq) in 2008, representing 6.2% growth in comparison to the 1990 level (the base year of the Kyoto Protocol), and a 12.2% disparity compared to the 6% reduction target set up under the first commitment period of the Kyoto Protocol. They also found that CO_2 accounted for 94% of Japan's GHG emissions over the period 1990 to 2008. (This percentage had risen from 91% in 1990 to 95% in 2008.) The historical emission data shows that in Japan energy conversion was the largest emitting sector, followed by the industrial sector, contributing a combined 65% of Japan's total GHG emissions over the period 1990 to 2008. The third-largest driver of GHG emissions is transportation at 35%.

Olivier et al. (2017) also looked at the Emission Database for Global Atmospheric Research (EDGAR), version 3, which is a set of global anthropogenic emission inventories of various trace gases developed by the National Institute for Public Health and Environment and the Netherlands Organisation for Applied Scientific Research in collaboration with the Global Emission Inventory Activity of the International Geosphere-Biosphere Programme, providing direct GHG emission data for the period 1970 to 1995 and for ozone precursors and SO_2 for the period 1990 to 1995. They used these datasets for trend analysis of global emissions and atmospheric concentrations of trace gases, as well as for analysis of regional distributions of present global emissions. Their study showed that, in the year 2000, non-CO_2 GHG emissions contributed about 18% to global total anthropogenic GHG emissions. Globally, energy has accounted for 70% as the largest source of anthropogenic GHG emissions, mainly from CO_2 emitted by fuel combustion (63%) and from agriculture (CH_4 and N_2O each contributing 15%). Some of the more marginal contributors were found to be biomass-burning, representing 8% of total emissions, primarily due to deforestation in developing countries, and CO_2 produced from cement production, representing 2% of total emissions. Globally, agriculture at 43% is the largest man-made source of CH_4, mainly from enteric fermentation by animals (25%) and rice cultivation (12%), with animal waste (3%) and savanna burning (3%) being less significant contributors. Other major sources of methane are energy production and transmission (29%), mainly from coal production (11%) and gas production and transmission (11%), with a smaller contribution from oil production (3%), while waste handling presently contributes about 18%, of which 11% is from wastewater and 7% from landfills. Their study also identified agriculture as the largest driver of N_2O at 84%, mainly from animal waste from grazing animals (22%), crop production (13%), the use of synthetic fertilizers (12%), animal manure collected and used as fertilizer (11%), and animal waste in stables (5%). Indirect N_2O generated by agriculture was found to have emitted 19%. These indirect emissions, it should be noted, arise from atmospheric deposition of nitrogen in ammonia (NH3) and N_2O emitted from agricultural sources, as well as from leaching and run-off of nitrogen in soils. A more marginal source in the manufacturing of nitric acid and adipic acid (4%), mostly in industrialized countries.

Some studies have looked at the trend of GHG emissions in specific sectors such as energy or livestock. For instance, De Ia Rue du Can and Price (2008) examined global and regional historical trends in energy use and CO_2 emissions over a 30-year looking at two of the scenarios produced by the IPCC's Special Report on Emissions Scenarios and contrasting with projections for the next 30 years. They compiled data for the purpose of examining CO_2 emissions related to three primary end-use demand sectors: industry, buildings, and transportation, drawing a distinction between final and primary energy consumption. They defined final energy consumption as encompassing the energy directly consumed by the end-user, whereas primary energy consumption represents final consumption plus the energy that was necessary to produce secondary energy, such as energy transformation losses. Moreover, they presented a methodology to calculate primary energy and CO_2 emissions at the sector level, representing the full energy and emissions due to sectoral activities.

Pathak (2015) presented a study looking at trends GHG emission from India's agricultural sector as well as mitigation planning, asserting that the agricultural sector warrants further investigation due to the increasing growth of GHG emissions, which have a considerable impact on crops, livestock, and fisheries, and also given the significant contribution of this sector to the greenhouse effect through the emissions of CO_2, CH_4, and N_2O. This study found that, in 2010, the Indian agricultural sector produced about 420 Mt CO_2-eq. Enteric fermentation accounted for 56% of the emission, followed by agricultural soil (23%) and rice fields (18%), while on-farm burning of crop residues and manure management contributed 2% and 1% of the emission, respectively. Furthermore, during the period 1970 to 2010, GHG emissions from the Indian agricultural sector experienced an increase of about 75%. The increasing use of fertilizers and other agri-inputs and the rising population of livestock were the major drivers of this increase. The relative contribution of Indian agriculture to total GHG emissions from all sectors, however, was found to have decreased from 33% in 1970 to 18% in 2010. Pathak also suggested mitigation planning for CH_4 and N_2O based on changes in land-use management and enhancing input-use efficiency.

GHG emissions have a significant influence on daily life and the environment in which we live, and many studies have focused on these impacts in different areas and sectors. Frölicher and Joos (2010) quantified the reversibility and irreversibility of GHG emission impacts by comparing anthropogenically-forced regional changes with internal, unforced climate variability. They employed a coupled carbon cycle-climate model to investigate the long-term impacts of 21st century GHG emissions on climate, ocean acidification, and carbon-climate feedbacks. They also concluded that emission trading schemes related to the Kyoto Protocol should not permit trading between emissions of relatively short-lived agents and CO_2, given the irreversible impacts of anthropogenic carbon emissions.

Bailis et al. (2005) analyzed the mortality impacts and GHG emissions by household energy use in Africa. Under a business-as-usual (BAU) scenario, they showed that household indoor air pollution would lead to an estimated 9.8 million premature deaths by the year 2030. They calculated that gradual and rapid transitions to charcoal would delay 1.0 million and 2.8 million deaths, respectively; similar transitions to petroleum fuels would delay 1.3 million and 3.7 million deaths. They projected that cumulative BAU GHG emissions will be 6.7 billion tonnes of carbon by 2050, representing 5.6% of Africa's total emissions in 2050. Large shifts to the use of fossil fuels would reduce GHG emissions by 1 to 10%. They also projected that charcoal-intensive future scenarios using current practices will increase emissions by 140% to 190%, while this increase can be reduced to 5% to 36% using currently available technologies for sustainable production (or potentially by even more by investing in technological innovation).

Greenblatt (2015) examined policy and technology scenarios for California in which they probed GHG emissions in 2020 and 2030. Using CALGAPS, a new validated model simulating GHG and criteria pollutant emissions in California from 2010 to 2050, four scenarios were developed: Committed Policies (S1), Uncommitted Policies (S2), Potential Policy and Technology Futures (S3), and Counterfactual (S0)—which omit all GHG policies, accompanied by forty-nine individual policies. For S1–S3, GHG emissions fall below the target of 427 Mt CO_2-eq/ yr (AB 32 policy 2020), showing that committed policies may be sufficient to meet mandated reductions. In 2030, emissions are projected to range from 211 to 428 Mt CO_2-eq yr $^{-1}$, suggesting that outcomes over the next two decades will be greatly affected by the policy decisions of today. A sensitivity analysis has been conducted to study the GHG impact of removing each policy individually was calculated, as well as the impact of removing groups of related policies. The uncertainty analysis has also conducted using the Monte Carlo simulation to explore variations in key uncertain parameters. Comparisons of results were made to previous studies, and shortcomings of the paper and possible remedies were discussed.

Boehlert et al. (2016) discussed the significant effects of climate change on hydropower generation due to changes in the magnitude and seasonality of river runoff and increases in reservoir evaporation, which leads to economic consequences through both producer revenues and consumer expenditures. It is in this context that they focused on analyzing the physical and economic effects of changes in hydropower generation for the contiguous U. S. in futures with and without global-scale GHG mitigation, and across patterns from 18 General Circulation Models. Using a monthly water resource system model of 2,119 river basins that route simulated river runoff through reservoirs and allocate water to potentially conflicting and climate-dependent demands, they provided a first-order estimate of the effects of different projected emissions outcomes on hydropower generation and monetized these impacts using outputs from an electric sector planning model for over 500 of the largest U.S. hydropower facilities. They found that, due to generally rising river runoff under higher emissions scenarios in the Pacific Northwest, climate change is likely to increase overall hydropower generation in the contiguous U.S. In this context, during low flow months, generation falls with increasing emissions, potentially threatening the estimated low flow, firm energy from hydropower. Although global GHG mitigation slows the growth of hydropower generation, the higher value placed on carbon-free hydropower can be expected to lead to annual economic benefits ranging from $1.8 billion to $4.3 billion. The present value of these benefits to the U.S. from global GHG mitigation, discounted at 3%, is $34 to $45 billion over the period 2015 to 2050.

Jørgensen et al. (2014) introduced the climate tipping impact category, representing the climate tipping potential (CTP) of GHG emissions, which in turn is related to climate target. The climate tipping impact category should be considered as supplementary to the global warming impact category. The CTP of all the assessed GHGs increases as the emission time approaches the target time, resulting in a rapid decrease in remaining atmospheric capacity and thus the increasing potential impact of GHG emissions. The CTP of a GHG, it should be noted, depends not only on the properties of the GHG but also on the selected climatic target level and background scenario for atmospheric GHG concentration development. CTP is characterized for three main GHGs, CO_2, CH_4 and N_2O, in order to enable direct application in life cycle assessment (LCA). The authors concluded that the CTP metric distinguishes various GHG emission effects in terms of their contribution to exceeding a short-term target and highlights their growing importance while approaching a climatic target level, in turn leading to an increased emphasis on avoiding further GHG emissions in order to keep below the target level. CTP can, in this respect, be considered to be as beneficial to the short-term target as it is to long-term targets. The climate tipping impact category is also useful for assessing climate change impacts in LCA, representing the long-term climate change impacts, and illustrating the value of LCA as a decision support tool for climate change mitigation.

Zeman et al. (2002) reviewed the GHG emissions impacts of the composting process as a major solution to mitigating these gases in waste management. Different composting scenarios were examined by various studies to model waste management. They characterized the major role not only of CH_4 and N_2O in their various forms as global pollutants, but also of solid waste, recycling, and composting community owing to their energy savings potential, carbon storage potential, and impact both directly and indirectly on public health.

The GHG Protocol Corporate Standard which establishes comprehensive global standardized frameworks to evaluate and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions, classifies GHG emissions into three ‘scopes’, where Scope 1 emissions are direct emissions from owned or controlled sources, Scope 2 emissions are indirect emissions from the generation of purchased energy, and Scope 3 emissions are all indirect emissions not included in scope 2 (Fong et al.). The scopes framework helps to differentiate emissions occurring physically within a city (scope 1), from those occurring outside the city (scope 3) and from the use of electricity, steam, and/or heating/cooling supplied by grids which may or may not cross city boundaries (scope 2). Scope 1 emissions may also be termed “territorial” emissions because they occur directly within the territory defined by the geographic boundary.

Bastianoni et al. (2004) underscored the necessity of assessments that investigate sources of GHG emissions in order to mitigate the greenhouse effect and halt global warming. Tajima et al. (2004), meanwhile, introduced an effective process for capturing and separating these gases from anthropogenic sources as an option for GHG reduction and removing, that is why the debate has aroused serious arguments on anthropogenic GHG sources. Rosa and Dietz (2012) identified human activity as the primary contributing factor to enhancing climate change, where a growing global population and increasing production and consumption lead to increased GHG emissions. Cartalis et al. (2001) stated that billions of tonnes of CO_2 are released into the Earth’s atmosphere as a result of consumption of natural resources and that CH_4, N_2O, and chlorofluorocarbons are the principal emissions released through human activities. The atmospheric concentrations of GHGs have consequently increased, with considerable impacts on the global climate and on surface temperature. In fact, high consumption of fuels such as oil and coal for human activities has been the primary driver of GHG emissions (Gomes et al., 2008). Kates et al. (2007) identified fossil fuel production and burning (manufacturing, electricity generation, transportation, and household heating), forestry and agriculture (livestock, wetlands, fertilizers, land clearing, timber production), waste disposal (landfills and incineration), and ozone-depleting chemical (ODC) manufacture and use as the principal contributors of GHG emissions among human activities.

Listowski et al. (2011) identified the causes of GHG emissions brought on by human activities as well as emissions from burning fuel as including emissions from wastewater discharge, sewage collection and wastewater treatment plants and associated activities. For instance, the concentrations of CO_2 increased from roughly 280 parts per million by volume (ppmv) in the pre-industrial age to 372.3 ppmv in 2001 and it is anticipated to keep rising at about 0.5% per year, whereas current CH_4 atmospheric concentration is increasing at a rate of 0.02 ppmv per year. Moreover, the annual sources of N_2O from the surface of the Earth have increased by about 40–50% over pre-industrial levels (Gupta and Singh, 2012).

Bogner et al. (2008) reported that GHG emissions from post-consumer waste and wastewater are a small contributor (about 3%) to total global anthropogenic GHG emissions. Emissions for 2004-2005 totaled 1.4 Gt CO_2-eq in year -1 relative to total emissions from all sectors of 49 Gt CO_2-eq in year 1 (including CO_2, CH_4, N_2O, and F-gases normalized according to their 100-year global warming potential (GWP)). The CH_4 from landfills and wastewater collectively accounted for about 90% of waste sector emissions, or about 18% of global anthropogenic methane emissions. Wastewater N_2O and CO_2 from the incineration of waste containing fossil carbon (plastics; synthetic textiles) were also reported as minor sources.

Gupta and Singh (2012) investigated the GHG emissions produced by wastewater treatment plants. Wastewater treatment is based on natural processes and provides a high removal of BOD, COD, organic carbon, nutrients and pathogenic microorganisms from wastewater. A significant amount of GHGs mainly CH_4 and N_2O are generated by wastewater treatment that is why reducing these emissions from the treatment process plays a key role in global warming. On the other hand, wastewater treatment plants allow recovering energy, and nutrients, thus the reuse of treated wastewater in developing and developed countries can be appropriated. Hence, the understanding and estimation of the GHG emission pathways of the wastewater treatment plant are essential to tackling this challenge.

Another human activity contributing significantly to GHG emissions is the transportation sector, which can be further divided into different sectors according to vehicle type and mode usage for the purpose of further investigation. For instance, Ong et al. (2012) assessed GHG emissions from transportation for a case study of Malaysia. They asserted that the transportation sector is one of the major components of globalization and makes a vital contribution to the economy. Moreover, it has become a major part of daily activities around the world. However, this activity not only consumes a high rate of energy, primarily non-renewable energy but also is responsible for a large and growing share of emissions. One of the primary concerns in this regard is the GHG emission of CO_2 and air pollutants such as NOx and particulates. CO_2 emissions generated by the transportation sector, due to its rapid growth, have been the subject of much concern within the scientific community worldwide. At the moment, the transportation sector accounts for 13.5% of global warming emissions. Indeed, transportation represents the fastest-growing carbon emissions of any economic sector. Proliferating numbers of automobiles are the key factor, as more than 600 million passenger cars are now on roads around the world.

Tubiello et al. (2013) pointed out that GHG emissions from agriculture, including crop and livestock production, forestry, and associated land-use changes, are responsible for a significant proportion of anthropogenic emissions, up to 30% according to the Intergovernmental Panel on Climate Change (IPCC). Agricultural lands occupy 37% of the earth's land surface. Fifty-two and 84 percent of global anthropogenic CH_4 and N_2O emissions, respectively, are produced by agriculture. Agricultural soils may also act as a sink or source for CO_2, but the net flux is small (Smith et al., 2008).

Wood and Cowie (2004) employed LCA to examine the GHG emissions (CO_2, N_2O, and CH_4) resulting from agricultural activities. Emissions of these gases may occur either directly during agricultural activities (e.g., cultivation and harvesting), or indirectly during the production and transport of required inputs (e.g., herbicides, pesticides, and fertilizers). In LCA, it should be noted, the environmental impacts of products and processes are analyzed from ‘cradle to grave’, such that both direct and indirect emissions from agricultural practices were included in their study. For instance, the production of fertilizers uses large amounts of energy and generates considerable GHG emissions. They mentioned that fertilizer production consumes approximately 1.2% of the world’s energy and is responsible for approximately 1.2% of the total GHG emissions. As such, fertilizer production is an important component of agricultural LCAs, where system boundaries are wide enough to include indirect emissions from agricultural inputs.

Combustion of fossil fuels plays a key role in global warming issues that today human is faced (Hoel and Kverndokk, 1996). Bond et al. (2004) looked at the global impacts of human activities and burning fossil fuels and noted that CH_4 and N_2O are significantly increasing in the atmosphere as a result of fossil fuel combustion.

2.2. GHG Emissions from Urban Areas

GHGs can be produced from a broad range of anthropogenic activities at different spatial and temporal scales (Li et al., 2018). To be able to take mitigating actions, it is important not only to identify the sources of GHG emissions but also to localize where these gases are emitted

(Bastianoni et al., 2004), i.e. where individuals live and work and their local activities are happening and contribute to global change (Kates and Torrie, 1998). Gomes et al. (2008) suggested performing exhaustive emission inventories, not only at a national level but also on regional and local scales in order to obtain more accurate results with respect to each area and then determine solutions for GHG reduction which are suited to the specific regions. In this regard, the highest energy production and consumption are attributed to cities due to their high concentration of population and the need to meet the demands of transport, industrial and commercial activities, and heating and cooling. In addition, owing to the population concentration, solid wastes and domestic, commercial and industrial effluents are produced primarily in urban agglomerations (Schmidt Dubeux and Rovere, 2007). In particular, emission from urban areas is a significant source of GHGs.

Fifty-four percent of the global population lived in urban areas in 2014, and by 2050 this ratio is projected to increase to 66%. About 75% of energy consumption and 80% of GHG emissions globally can be attributed to urban activities (Hu et al., 2016). Cities are therefore playing an increasingly key role in GHG reduction policies and actions. In this regard, Hillman and Ramaswami (2010) specified the average GHG contributions of different human activity sectors, including building/facility energy use (47.1%), regional surface transport (20.8%), food production (14.7%), transport fuel production (6.4%), airline transport (4.8%), long-distance freight trucking (2.8%), cement production (2.2%), and water/wastewater/waste processing (1.3%).

The efforts of municipalities are crucial for achieving GHG reduction goals, and there are many studies in the literature which have assessed GHGs emitted in urban areas by different sectors, such as the study by Hillman and Ramaswami (2010) looking at the GHG emissions and energy use of eight U.S. cities. Their study provided not only the first view of metrics for average energy, water, material use, travel demand, and associated GHG emissions across a few different U.S. cities but also a snapshot of variation in these parameters across cities. They noted that, with more than one thousand cities worldwide have pledged to mitigate GHG emissions at the local scale, of which 956 cities are in the United States alone. This is why the city-scale is becoming increasingly important in global climate action efforts. However, the smaller spatial scale of cities with the significant cross-boundary exchange of key goods and services, surface commuter travel, and airline travel has posed a challenge in developing a holistic accounting of GHG emissions associated with human demand for energy and materials in cities.

Gomes et al. (2008) evaluated GHG emissions related to electricity demand in solid and liquid waste treatment facilities in Oeiras, Portugal. The results obtained showed that 75% of the municipal emissions in 2003 were attributable to electricity. This study was improved with the aim of obtaining tools to base options and actions to be implemented by local authorities such as energy planning and also public information. The increase of greenhouse gases (GHG) emissions is an important and most concerning issue, where these emissions are the result of the high consumption of fossil fuels such as oil and coal. In order to help to overcome these arising problems and to determine appropriate reduction measures, it is necessary to perform exhaustive emission inventories, not only at a national level but also on regional and local scales. They also identified fossil fuels such as oil, coal, and natural gas burning for electricity production and its utilization in industry, deforestation, transportation systems, waste-burning as well as evolved gases from sanitary landfills as main contributors of CO_2.

Gurjar et al. (2004) developed a comprehensive emission inventory for Delhi, India, for the period 1990–2000 in support of air quality, atmospheric chemistry, and climate studies. Their results underscored the concentrations of GHG emissions in different sectors and compared them over the decade under study. Their study was also the first comprehensive and consistent emission inventory for Delhi, including a range of air pollutants and GHGs. They illustrated that power plants are the main source of SO_2, while the largest source of NOx (82%) and CO (86%) was the transportation sector. Agriculture accounted for the largest emission source of NH_3 and N_2O by 70% and 50%, respectively, while solid waste disposal is the main source of CH_4 at 80%. Their results showed that cities not only are increasingly being recognized as important sources of pollutants that can travel across the globe but also affect global atmospheric chemistry and climate, and their role in global inventories and atmospheric chemistry modeling will likely increase in the future.

Many studies have examined GHG emissions for different sectors. For instance, Kenworthy (2003) studied the impacts of transportation on climate change in cities, assessing the energy consumed by automobiles and the GHG emissions produced by this sector as a major motivation for evaluating transportation. This study, in addition to providing a global view of these issues, described a methodology and data sources, presenting results for a wide range of transportation and urban form characteristics of cities, summarized by different regions in the world and divided according to high and low-income areas. Data covered include urban infrastructure and wealth, vehicle ownership, private and public transport infrastructure and usage, public transport service, and modal split.

In another study, the major GHGs produced in wastewater treatment operations, CO_2, CH_4, and N_2O, were evaluated by Gupta and Singh (2012). Wastewater treatment plants (WWTPs) are based in natural processes and provide a high removal of BOD, COD, organic carbon, nutrients and pathogenic microorganisms from wastewater. Wastewater treatment generates a significant amount of greenhouse gases which the main GHG emissions produced by wastewater treatment are methane and nitrous oxide. Reducing these emissions from the treatment process and the contribution of the WWT processes to global warming is a major concern. On the other hand, WWTPs allow recovering energy, and nutrients, thus the reuse of treated wastewater in developing and developed countries can be an appropriate opportunity to mitigate GHG emissions produced by this sector.

Saidur et al. (2007) focused on the GHGs emitted by electricity generation in a case study in Malaysia, seeking solutions to reduce GHGs in this sector. Electricity generation, it should be noted, principally depends upon fossil fuels. In the upstream side of electricity generation, the study estimates the amount of greenhouse gases (GHGs) resulting from the burning of fossil fuels. Energy savings and reduction of GHGs have been considered on the downstream side. Energy consumption and emission production trend for household appliances have been presented for a period of 17 years (1999–2015) in this study. The study has found that refrigerator-freezer is the major energy-consuming appliance followed by air conditioners, washing machines, fans, rice cookers, and iron.

Municipal solid waste (MSW), meanwhile, generally includes degradable (paper, textiles, food waste, straw and yard waste), partially degradable (wood, disposable napkins, and sludge), and non-degradable materials (leather, plastics, rubbers, metals, glass, ash from burning of fuels such as coal, briquettes, or woods, dust, and electronic waste). Generally, MSW is managed by the collection it from residents and disposing of it at landfills. Anaerobic decomposition of MSW in landfills generates about 60% CH_4 and 40% CO_2 together with other trace gases. For this reason, the GHG emissions produced by MSW warrants attention, and since this percentage differs spatially depending waste composition, age, quantity, moisture content and ratio of hydrogen/oxygen availability at the time of decomposition, Jha et al. (2008) have assessed GHG emissions from municipal solid waste applying the methodology of the IPCC, employing a case study in Chennai, India.

There are some annual municipal GHG inventories available, and typically they are categorized by different sectors such as stationary energy, transportation, or mobilizing energy waste, although some are categorized by sources, such as gasoline, natural gas, oil. According to the GHG inventory for New York City, The City of New York (2017) quantified the GHG emissions produced in the city in 2017. According to their report, stationary sources, including natural gas, electricity and fuel oil, are the highest contributors to regional GHG emissions, and the energy used in New York City buildings was found to have generated 34.4 $MtCO_2eq$ in 2016, while natural gas was the largest driver of GHG emissions at 47% of building-based emissions, followed by electricity generation. They also found that the residential sector is the largest producer of GHG emissions in New York City, while 30% of citywide emissions are derived from the transportation sector (15.5 $MtCO_2eq$). On-road vehicles were found to be the largest source of emissions from this sector, accounting for 96% of emissions from transportation (29% citywide). Within this sector, vehicles that consume gasoline were found to be the primary contributor, accounting for 80% of transportation-based emissions.

2.3. Emission Assessment Methodology

The IPCC has conducted methodologies which have become common for GHG inventories. In addition to that of the IPCC, other methodologies mentioned in this study have been drawn from various publications and GHG inventories. For each sector, different methodologies are obtained based on the available data. For instance, in the transportation sector, there is a methodology according to the number of vehicles driven (Gurjar et al., 2004) on the boundary streets or fuel consumption of vehicles (Ong et al., 2012), but it depends on the available data.

Energy estimation

Energy is categorized by IPCC (2006) as either stationary combustion or mobile combustion. Stationary combustion mainly includes energy industries, heating and electricity, while mobile combustion focuses on transportation and civil aviation. Both of these categories can be estimated with the same equation as follows:

$$\text{Emissions}_{\text{GHG, fuel}} = \text{Fuel consumption}_{\text{fuel}} \times \text{Emission Factor}_{\text{GHG, fuel}} \tag{2.1}$$

where:
$\text{Emissions}_{\text{GHG, fuel}}$ = emissions of a given GHG by type of fuel
$\text{Fuel Consumption}_{\text{fuel}}$ = amount of fuel combusted
$\text{Emission Factor}_{\text{GHG, fuel}}$ = default emission factor of a given GHG by type of fuel

Yip et al. (2017) estimated the GHG of Regina, Saskatchewan, by multiplying the total electricity generated using a given fossil fuel type (coal, natural gas) in megawatt-hours by the emissions factor of a fossil fuel generating station type (t CO_2-eq/MWh) and by the total electricity generated by a given fossil fuel type (coal, natural gas) in megawatt-hours in order to obtain the emission intensity. They used another calculation to achieve the GHG emissions from electricity generation, including emission intensity, the total electrical energy usage per end-use sector, and the proportion of electricity lost in transmission and distribution.

Saidur et al. (2007) evaluated the GHG emissions produced by electricity generation in the case study of Malaysian households, showing that the amount of electrical energy consumed by an appliance can be determined by multiplying the number of appliances of a particular type by the average power rating and the duration of usage. To estimate the amount of GHGs released for generation of electricity from fossil fuels in their methodology, the fossil fuel emission for a unit of electricity generation of fuel type (n) is added to the percentage of electricity generation in year (i) of fuel type (n), the obtained answer is multiplied by the Electricity production in year (i).

Schmidt Dubeux and Rovere (2007) assessed municipal GHG emissions from different sectors for Rio de Janeiro using an adaptation of the IPCC method for the Brazilian cities. This sector was evaluated based on both CO_2 and CH_4 although, these can be converted to CO_2-eq by multiplying them by the GWP value. The methodology applied encompassed fuel consumption, emission factor, stored carbon, unoxidized carbon ratio, and then all the above-mentioned factors are multiplied by 44/12, which is the conversion factor from carbon to CO_2. This study also summarized a report of the experience in building an inventory from secondary data and building up scenarios that have been undertaken in Rio de Janeiro, Brazil, estimating the CH_4 produced by natural gas by multiplying the gas consumption by the emission factor.

Singh et al. (2017) estimated GHG emissions from wastewater treatment in India. The methodology they used is based on IPCC guidelines for national GHG inventories. They estimated all emissions of CO_2, CH_4, and N_2O using the following formula:

$$\text{GHG emissions} = \text{activity data} \times \text{emission factor} \quad (2.2)$$

Schmidt Dubeux and Rovere (2007) which summarized a report of the experience in making an inventory from secondary data and building up scenarios that have been undertaken in Rio de Janeiro, Brazil, have estimated CH_4 produced by natural gas through multiplying the gas consumption by the emission factor.

Industrial estimation

IPCC (2006) has divided industry emissions into three components: chemical industry emissions, metal industry emissions, and electronics industry emissions. Here the calculation of CO_2 emissions directly from cement production is cited as an example to demonstrate the methodologies, where emissions of CO_2 from cement production is obtained based on tonnes by multiplying the weight (mass) of cement produced by the clinker fraction of cement, and the result is subtracted from the imports for consumption of clinker and then added to the exports of clinker, and then that result multiplied by the emission factor for clinker in that particular cement, expressed as tonnes of CO_2 per tonne of clinker.

Kennedy et al. (2010) developed a methodology for heating and industrial fuels. In this category, emissions are primarily produced by fossil fuels used for heating in buildings, e.g., space heating, water heating, and cooking. Also included are fossil fuels used by CHP facilities within cities (mainly natural gas and oil) and, where data are available, fossil fuels combusted by industry. GHG emissions are determined by multiplying the energy contents of fuels used by the emission factor of the given fuel.

Transport estimation

CO_2 is typically the main contributor considered in inventories of GHGs, while evaporative emissions are not likely to be significant. A simple, fuel-based approach will estimate emissions of CO_2 accurately enough, provided that the fuel consumption is known. In general, total emissions from road transportation are estimated by multiplying the emission factor as a mass per unit of activity rate by the activity rate (fuel consumed or distance traveled), then adding extra emissions due to cold starts and evaporation. This method depends on fuel type (gasoline, diesel, LPG, etc.), vehicle type (passenger car, light-duty truck, bus, etc.), emission control, and road type or vehicle speed.

Another approach which can be applied for the estimation of GHG emissions from road transportation is based on fuel consumption. While the total of each fuel used by road transportation may be well known, the amounts used by each vehicle type may need to be further explored. Furthermore, different fuels, such as LPG, CNG, and methanol, may be consumed in different jurisdictions. It is important to know how much of each of these fuels are used by transport vehicles (IPCC, 2006).

Yip et al. (2017) estimated the emissions from road transportation based on fuel consumption by multiplying the number of units of a given vehicle and technology type from a given model year currently in operation by the annual vehicle distance traveled by each vehicle type and the energy consumption of the vehicle type and the emissions intensity of the energy source. Lenzen (1999), similarly, assessed the GHG emissions produced by Australia's transportation sector by multiplying the amount of fuel consumed by the GHG content.

Gurjar et al. (2004) used the number of vehicles approach to obtain the GHGs emitted by transportation. They multiplied the number of vehicles by the distance traveled in a year for different vehicle types, and by the emission rate of the given compound, and the kilometers driven per vehicle in order to obtain emissions of a given compound.

Waste estimation

CH_4 is the most significant emission from waste, and it is generated as a result of the degradation of organic material under anaerobic conditions. Part of the CH_4 generated is oxidized in the cover of the SWDs or can be recovered for energy or flaring. The CH_4 actually emitted from the SWDS will hence be smaller than the amount generated, the recovered CH_4 in year *T* is subtracted from the cumulative of methane generation in year (T) and the obtained results is multiplied by the result from the subtraction of the oxidation factor in year (T) from 1 (IPCC, 2006).

Kumar et al. (2004) developed a methodology to estimate GHG emissions by MSW in a case study of Delhi, India. In their methodology, the total SW reached in the year (T) is multiplied by the CH_4 correction factor (taken as 0.4 for unmanaged landfill site) and, based on the composition of waste for Delhi, the degradable organic carbon in solid waste value is taken as 0.15. The default value for dissimilated organic fraction and the fraction of CH_4 are 77% and 50%, respectively. The value for CH_4 recovery factor and oxidation factor is 0. The emission coefficient arrived at in estimating CH_4 emission using is thus 0.0308.

In a related study, Yip et al. (2017) assessed the emissions from landfills by multiplying the mass of degradable organic carbon decomposed by the fraction (by volume) of CH_4 in landfill gas, which in turn is subtracted from the amount of landfill gas collected. This result is then multiplied by the result of subtracting 1 of the oxidation factor of the emitted landfill gas, where GWP100 is the global warming rate multiplied by the GWP based on a 100-year time frame.

Wastewater estimation

IPCC (2006) presented an equation to estimate CH_4 emissions from domestic wastewater which included the total organics in wastewater in inventory year, organic component removed as sludge in inventory year and proportion of population in income group named (i) in inventory year shown by the degree of utilization of treatment/discharge pathway or system called (j), for each income group proportion (i) in the inventory year. In this study(i) shows the income group (rural, urban high income, urban low income), while (j) indicates the treatment/discharge pathway or system.

Emission from wastewater can also be calculated by multiplying the amount of treated wastewater by the national emission factor (Gomes et al., 2008). Schmidt Dubeux and Rovere (2007) calculated the CH_4 emitted by wastewater treatment by multiplying the organic matter produced biochemical oxygen demand (BOD) for domestic and commercial wastewater and sludge or COD minus chemical oxygen demand for industrial wastewater and sludge, by the maximum CH_4-producing capacity of 25% which is default value, and the CH_4 correction factor, , and the emission factor, and the then total amount of CH_4 recovered or flared from wastewater in CH_4 is subtracted from the result obtained by the multiplication.

Carbon sequestration estimation

Although all reviewed sectors above are producing CO_2-eq, there is still one source in each city which is able to capture GHG emissions. Some studies focused on capturing GHG emissions by greenspace. The methodology developed by Yip et al. (2017), for instance, estimates carbon offset by multiplying the number of trees by the absorption factor.

2.4. Literature Review Summary

In light of rising concerns about climate change resulting from increasing GHG emissions, many studies in recent years have explored this topic, identifying human activities as the main source of these emissions and calling for further studies to not only specify the sources but also localize these emissions. Since the growing majority of the world's population lives in urban areas, the largest share of GHG emissions has been attributed to cities, and thus many studies have concentrated on municipal GHG emissions. The first step to reducing GHG emissions, it should be noted, is the identification and assessment of the contributing factors and the effect of each factor. The first methodology in this regard was developed by the IPCC, and then subsequent studies applied their methodology to estimate GHG emissions for different jurisdictions, with some researchers developing their own methods in various sectors such as transportation, waste, wastewater, and energy. All of these methodologies can be formed differently based on the available data and to obtain accurate results details for each contributing factor should also be provided.

CHAPTER 3. METHODOLOGY FOR URBAN GHG EMISSION ANALYSIS

3.1. Urban GHG Emission Sources

Cities play an important role the modern society. GHGs can be derived from many sources in the urban area. As shown in Figure 3-1 the main sources of GHGs in urban areas typically include emissions from transportation, heating, electricity generation, and waste processing.

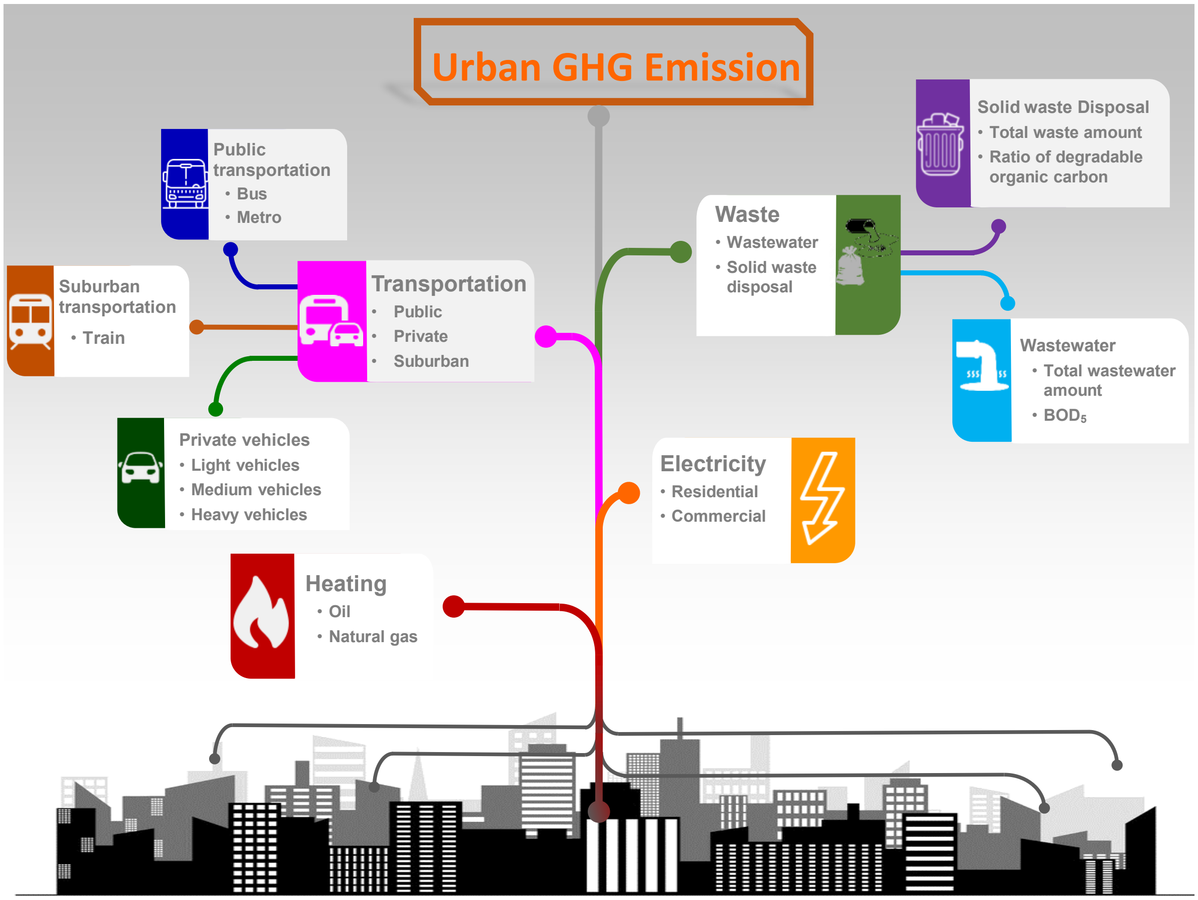

Figure 3-1 Urban GHG emission sources.

3.2. Emissions from Urban Public Transportation

Public transportation is considered as an effective way to reduce overall GHG emsission, although fossil fuel such as gasoline and natural gas is still consumed in this process. Substantial resources have been used to meet the transportation needs of the urban population. The following has been developed based on different fuels to consider all GHG emissions produced by public transportation. The significant point to apply the below methodology in different fuels is to use the same unit for the amount of fuel consumption as the unit of emission factor. The GHG emissions in this section can be calculated based on the consumption of different energy types.

$$E\_UPT = \sum AM\_ENERGY_i \times EF\_ENERGY_i \qquad (3.1)$$

E_UPT: GHG emission from urban public transportation (kg CO_2-eq)
AM_ENERGY: The amount of energy consumed (GJ)
EF_ENERGY: Emission factor of the energy (kg CO_2-eq/GJ)
i: Energy types including diesel, gasoline, electricity, biodiesel, etc.

3.3. Emissions from Suburban Public Transportation

In urban areas, there is a suburban public transportation network such as commuter trains to connect urban and suburban areas. They mostly include trains, buses, and taxies which sometimes are neglected in the municipal assessment of GHG emissions, even though their routes pass within the city and this network GHG production should be included in the urban GHG emission assessment (Zahabi et al., 2012). However they play the main role to mitigate GHG emissions by the reduction of number of private vehicles on roads, burning the enormous amount of fossil fuel should be considered in assessment of GHG emissions.

$$E\_SPT= \sum (AW_{j,k} \times TTD_{j,k}) \times EF\_ SPTN_j \qquad (3.2)$$

E_SPT: GHG emission from suburban public transportation (kg CO_2-eq)
AW: Average weight of suburban public transportation vessel (tonne)
TTD: Total travel distance of suburban public transportation vessel (km)
EF_SPTN: Emission factor of suburban public transportation type (kg CO_2-eq/tonne-km)
j: Suburban public transportation types

k: Suburban public transportation routes

3.4. Emissions from Private Vehicles

One of the largest drivers of urban GHGs emissions is vehicles and while increasing number of private vehicles on the streets their role would be greater. In this study to clarify the role of each sector, the contribution factors considered as separated as they could, that is why vehicles divided into three parts such as urban public transportation, suburban public transportation and private vehicles. Moreover, private vehicles categorized into three categories defined by the weight of vehicles such as light vehicles (less than 4,500 kg, e.g. cars, vans, light pickups, station wagon, van, SUV, and motorcycles), medium vehicles (between 4,500 kg and 9,000 kg, e.g. heavy-duty pickups and medium size work trucks), and heavy vehicles (greater than 9,000 kg, e.g. garbage trucks and tandem dump trucks). The different methodologies can be applied in this section. One approach would be based on the number of vehicles and another one based on fossil fuel amount consumed by vehicles. The methodology indicated in this study is according to the number of vehicles registered in the area boundary.

$$E\_VEH = \sum (N\_VEH_m \times ATD_m \times FE\_VEH) \times EF\_FUEL \tag{3.3}$$

E_VEH: GHG emission from vehicles (kg CO_2-eq)

N_VEH: Number of vehicles

ATD_VEH: Average travel distance per vehicle (km/vehicle)

FE_VEH: Fuel efficiency (L/km)

EF_FUEL: Emission factor of fuel consumption (kg CO_2-eq /L)

m: Vehicle type

3.5. Emissions from Fuel-Based Heating

To meet the living requirements, heating provided in urban areas can be one of the most significant contributing factors to urban GHGs emissions. Natural gas is often used as a major fuel type for heating in the municipal area. Burning natural gas to provide heating, produces greenhouse gases such as CO_2, CH_4, and N_2O. Some other fuel types such as heating oil are also used in some areas as well as electricity, although using electricity with the aim of heating should be considered in the electricity section. The consumption of these fuels for heating will be associated with the generation of GHGs. The methodology developed in this study can be applied for any kind of fuel consumed for heating-target. The GHGs from heating can be calculated as follows.

$$E\_HEAT = \sum AM\_HEAT_n \times EF\_HEAT_n \tag{3.4}$$

E_HEAT: GHG emissions from heating (kg CO_2-eq)
AM_HEAT: Total amount of heating fuel (m^3 or GJ)
EF_HEAT: Emission factor of heating fuel (kg CO_2-eq/m3 or kg CO_2-eq/GJ)
n: heating fuel types

3.6. Emissions from Electricity

Electricity is extensively consumed for residential, commercial and industrial activities in urban areas. GHG emission is associated with the generation of electricity and it can be regarded as the indirect emission for the urban system. The electricity can be produced from power plants using natural gas, coal, fuel oil, geothermal energy, solar power, and hydropower plants, that is why the ratio of electricity generation should be considered in the methodology. Definitely, the greenhouse gas produced by the burning of fossil fuel (coal, natural gases) is the main component in this section and electricity generated by hydropower would have the least contribution ratio to GHGs emissions. The total GHG emission from electricity is as follows.

$$E\_ELEC = \sum AM\_ELEC_s \times RATIO\_ELEC_t \times EF\_EGS_t \tag{3.5}$$

E_ELEC: GHG emission from electricity (kg CO_2-eq)
AM_ELEC: Amount of electricity consumption in section (GWh)
RATIO_ELEC: Ratio of electricity generation from different sources
EF_EGS: Emission factor in electricity generation source (kg CO_2-eq/GWH)
s: Sections of electricity consumption in residential, institutional, commercial and industrial sectors.
t: Electricity generation sources including hydropower, thermopower, solar power, etc.

3.7. Emissions from Solid Waste Disposal

The disposal and treatment of solid waste can result in the emissions of several GHGs. In this study, the methodology developed to model the waste sector uses the greenhouse gas emission of the landfill as the main effect. The major GHG released from this process is CH_4 and CO_2 and it is emitted during the breakdown of organic matter from solid waste in the disposal process. The GHGs produced from solid waste disposal can be evaluated as follows.

$$E\_SWD = [(AM\_MSW \times DOC\_SW \times F\_DOC \times MCF \times F\_MLG \times 16/12) – RM] \times (1\text{-}OF) \times GWP\_CH_4 \quad (3.6)$$

E_SWD: GHG emission from solid waste disposal (kg CO_2-eq)
AM_MSW: Total amount of municipal solid waste in the year (kg waste)
DOC_SW: Degradable organic carbon in solid waste (kg carbon/kg waste)
F_DOC: Fraction of degradable organic carbon dissimilated
MCF: Methane correction factor
F_MLG: Fraction of methane in landfill gas
16/12: Conversion of C to CH_4
RM: Recovered methane (kg CH_4)
OF: Oxidation factor
GWP_CH_4 : Global warming potential of CH_4 (kg CO_2-eq/kg CH_4)

3.8. Emissions from Wastewater Treatment

High removal of BOD, COD, organic carbon, nutrients and pathogenic microorganisms from wastewater can be provided by wastewater treatment plants (WWTPs). CO_2 and CH_4 Production result from the breakdown of organic matter in the activated sludge process and some through the primary clarifiers, degradation of nitrogen components in the wastewater also result in N_2O production (Gupta and Singh, 2012). The operation of municipal wastewater treatment plants is also associated with the emission of GHGs. methane (CH_4) can be produced from wastewater when treated or disposed of anaerobically and nitrous oxide (N_2O) and Carbon dioxide (CO_2) emissions can be emitted from wastewater. Reducing these emissions from the treatment process and the contribution of the WWT processes to global warming is a major concern. The GHG emission from the wastewater treatment process can be calculated using the following equation.

$$E\_WT = E\_WT_{CH_4} + E\_WT_{N2O} \quad (3.7)$$

E_WT: GHG emission from wastewater treatment (kg CO_2-eq)

E_CH_4: Emission of CH_4 (kg CO_2-eq)

E_N_2O: Emission of N_2O (kg CO_2-eq)

$$E\_CH_4 = AM\_WW \times CBOD \times EF\_CH_4 \times GWP\_CH_4 \times 10^{-6} \quad (3.8)$$

AM_WW: Amount of wastewater (L)

CBOD: Concentration of BOD_5 in wastewater (mg/L)

EF_CH_4: Emission factor (kg CH_4/kg BOD_5)

$$E\_N_2O = AM\_WW \times CN \times EF\_N_2O \times GWP\_N_2O \times 1.57 \times 10^{-6} \quad (3.9)$$

CN: Concentration of nitrogen in wastewater (mg N/L)

EF_N_2O: Emission factor (kg N_2O-N/kg N)

GWP_N_2O: Global warming potential of N_2O (kg CO_2-eq/kg N_2O)

1.57: Conversion factor of kg N_2O-N into kg N_2O

CHAPTER 4. GHG EMISSION INVENTORY ANALYSIS

4.1. Boundary of GHG Emission Analysis

Montréal, Québec, incorporated as a city in 1832 and with a population of 1,765,616 (Municipal Benchmarking Network Canada, 2016), is Canada's second-largest city and home to nearly half of Québec's population. It is the largest metropolis in the province and is the second-most populous city in Canada for a century and a half. It is located at the confluence of the St. Lawrence and Ottawa rivers and in southwestern Québec on Île de Montréal. Montréal is one of the centers of francophone culture in North America and a major industrial, commercial and financial center, railway and maritime bridgehead. It is one of the world's great cities and enjoys international acclaim. The land area of Montréal is 365.65 km^2 and the population density was 4,662.1/km^2. In 2016, there were 779,802 private dwellings occupied in Montréal (Ville), which represent a change of 2.6% from 2011 (Statistics Canada, 2019).

The climate and weather condition gives more introduction of the island, Summers in Montréal are warm and humid with a daily maximum average of 26 to 27 °C (79 to 81 °F) in July, while temperatures in excess of 30 °C (86 °F) are common. In the early and later parts of summer, this city experiences drier and windy weather. Winter is cold, snowy, windy, and, at times, icy weather, with a daily average ranging from −9 to −10.5 °C (16 to 13 °F) in January. However, some winter days rise above freezing, allowing for rain on an average of 4 days in January and February each. Usually, snow covering some or all bare ground lasts on average from the first or second week of December until the last week of March. While the air temperature does not fall below −30 °C (−22 °F) every year (The weather network, 2020).

Montréal and the mayors of a number of cities made a commitment to reduce GHG emissions by 30% by 2020 during the fourth Municipal leaders' Summit on Climate Change, held in December 2005, in Montréal. As the first step in this direction, in 2007 the Montréal adopted a plan to reduce its own GHG emissions by 20% by 2012

In this context, the Government of Canada (Government of Canada, 2017a) outlines the considerations for GHG reporting in Canada, specifying who must report and what information must be reported. As per their guidelines, all facilities that emit 10 kt CO_2-eq or more per year must submit a report. Since industrial emitters in Montréal are producing less than this threshold, this sector has not been required to report its emissions since 2016. Therefore, the sources that should be considered in Montréal are transportation, fuel-based heating, electricity, solid waste disposal, and wastewater treatment. In the present study, the boundary of Montréal Island as shown in Figure 4-1 was used for the emission assessment.

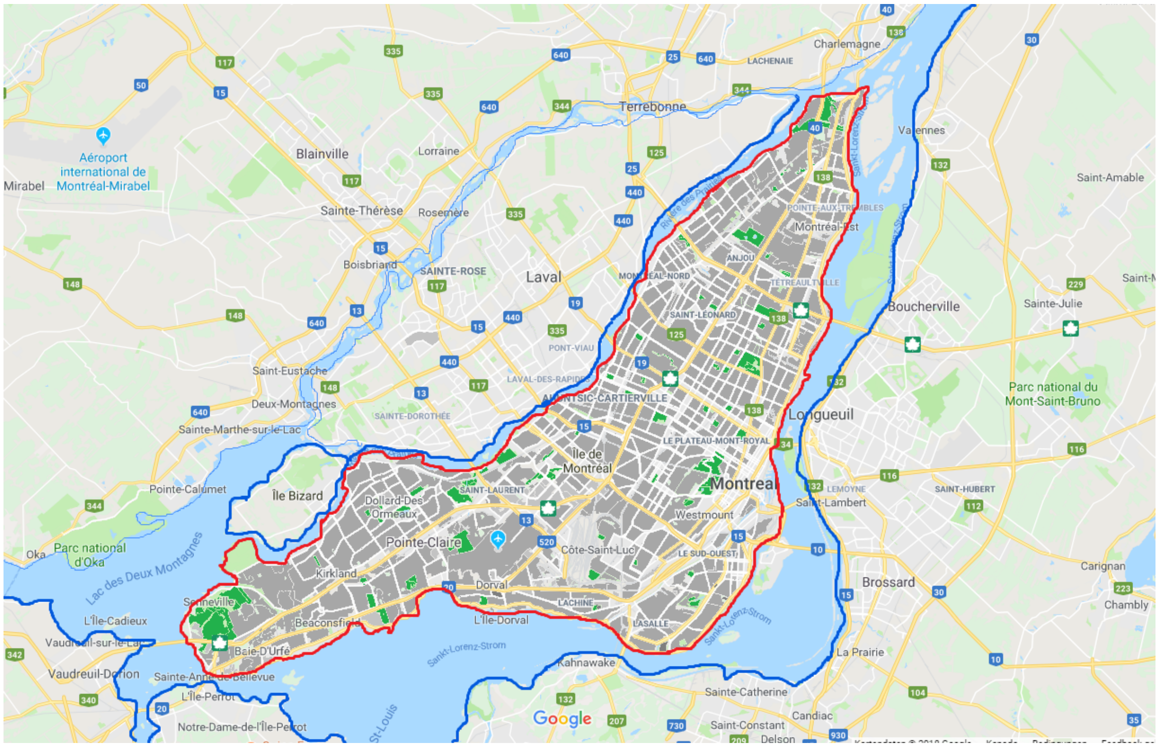

Figure 4-1 Boundary of Montréal Island (Google map).

4.2. Emissions from Urban Transportation Network

Montréal is one of Canada’s major metropolitan areas and has a well-developed and well-performing public transit network. Public transportation has been in operation in Montréal for over 150 years. In fact, the first tramways, which were horse-drawn at the time, began operating on the city’s streets on November 27, 1861. Although the company has changed its name several times and became a public corporation in 1951, it has always fulfilled its mission to provide Montréalers with a fast, reliable, economical transit service.

For the present study, the energy consumption of public transportation in Montréal was obtained from Société de transport de Montréal (STM) with respect to two different sectors, energy consumption by transit stations and vehicles. In the present study, to avoid any overlaps between electricity and natural gas, only the vehicle sector is considered. In this regard, both Energir and Hydro-Québec, the companies responsible for the distribution of natural gas and electricity in Montréal, respectively, have already published data on the usage for major industries such as STM or RTM (suburban transportation by train) in their annual reports. The data is categorized by fuel (e.g., diesel, gasoline, natural gas, hydropower, and biodiesel), although Energir reports that there is no public transport consuming natural gas, meaning that the fuels considered in this sector are diesel, gasoline, hydropower, and biodiesel and the amount these sourses of by transportation is represented in Table 4-1. The major fuel in the Montréal transportation network is diesel (Societe de Transport de Montreal STM, 2016). As with other cities in North America, efforts are underway to encourage other technologies such as diesel-electric hybrid bus technology and battery electric bus technology in order to reduce GHG emissions in this sector.

Table 4-1 Energy consumption by STM in 2016 (Societe de Transport de Montreal STM, 2016)

Indicator	**Amount**	**Unit**
Service offering	163,265	thousands of km traveled
Metro	79,299	thousands of km traveled
Surface network	83,965	thousands of km traveled
Total energy consumption	3,873.1	PJ (10^{15} joules)
Total energy consumption From non-renewable sources	2,378.7	PJ (10^{15} joules)
Total energy consumption From renewable sources	1,494.4	PJ (10^{15} joules)
Diesel	1,872	TJ
Gasoline	26	TJ
Electricity	1,434	TJ
Biodiesel	60	TJ
Total energy consumption per passenger-km	1,110	kJ
Total energy consumption per passenger-km	1,110	kJ
Total energy consumption per seat-km	307	kJ

Furthermore, the present study seeks to provide a comprehensive account of the sources of emission factors in different sectors. A table of emission factors is therefore provided in each sector which shows these factors based on different sources, different jurisdictions, and different units. This information is accompanied by references that enable researchers to find the required emission factor easily and quickly based on the location for which it is being estimated and the unit of the activity data. The method developed for this sector is based on fuel consumption by public transportation vehicles such as buses and subway trains. The total amount of fuel consumption is multiplied by the emission factor which is drawn from different data sources for different jurisdictions and units, shown in Table 4-2.

Table 4-2 Emission factors for fuel used in public transportation

Fuel type	**Amount (kg CO_2-eq /unit)**	**Unit**	**Location**	**Reference**
Gasoline	69.30	GJ	Portugal	(Agência Portuguesa do Ambiente, 2017)
	3,200	Mg	China	(Zhang et al., 2007)
Diesel	74.07	GJ	Portugal	(Agência Portuguesa do Ambiente, 2017)
	2.6712	Liter	Australia	(Australian Transport Assessment and Planning (ATAP), 2016)
	10.21	gallon		(U.S. EPA, 2018)
Biodiesel	71.42	GJ	Portugal	(Agência Portuguesa do Ambiente, 2017)
	9.45	gallon		(U.S. EPA, 2018)
Electricity	0.002-0.048	KWh		(Zhang et al., 2007)

Table 4-3 dedicates the amount of energy consumption over 10-year period from 2006 to 2015 in order to figure out the trend of GHG emissions produced by urban transportation network over the period. These energy consumption provided by annual reports of STM (Societe de Transport de Montreal STM, 2016) have been applied by the developed methodology to obtain GHG emissions. Figure 4-2 showing the ratios of energy consumption in Montréal in 2016, illustrates the primary source of urban public transportation in the city is diesel by 55% and the second source of energy for this sector is electricity with 42%.

Table 4-3 Energy consumption by STM from 2006 to 2015 (Societe de Transport de Montreal STM, 2016)

Energy consumption (TJ)	**Diesel**	**Gasoline**	**Electricity**	**Biodiesel**
2006	1,787	23	1,042	-
2007	1,697	31	1,237	1
2008	1,705	31	1,355	51
2009	1,822	30	1,343	65
2010	1,927	15	1,347	66
2011	1,997	24	1,368	67
2012	1,981	28	1,380	69
2013	1,974	24	1,394	66
2014	1,898	27	1,431	69
2015	1,856	25	1,442	76

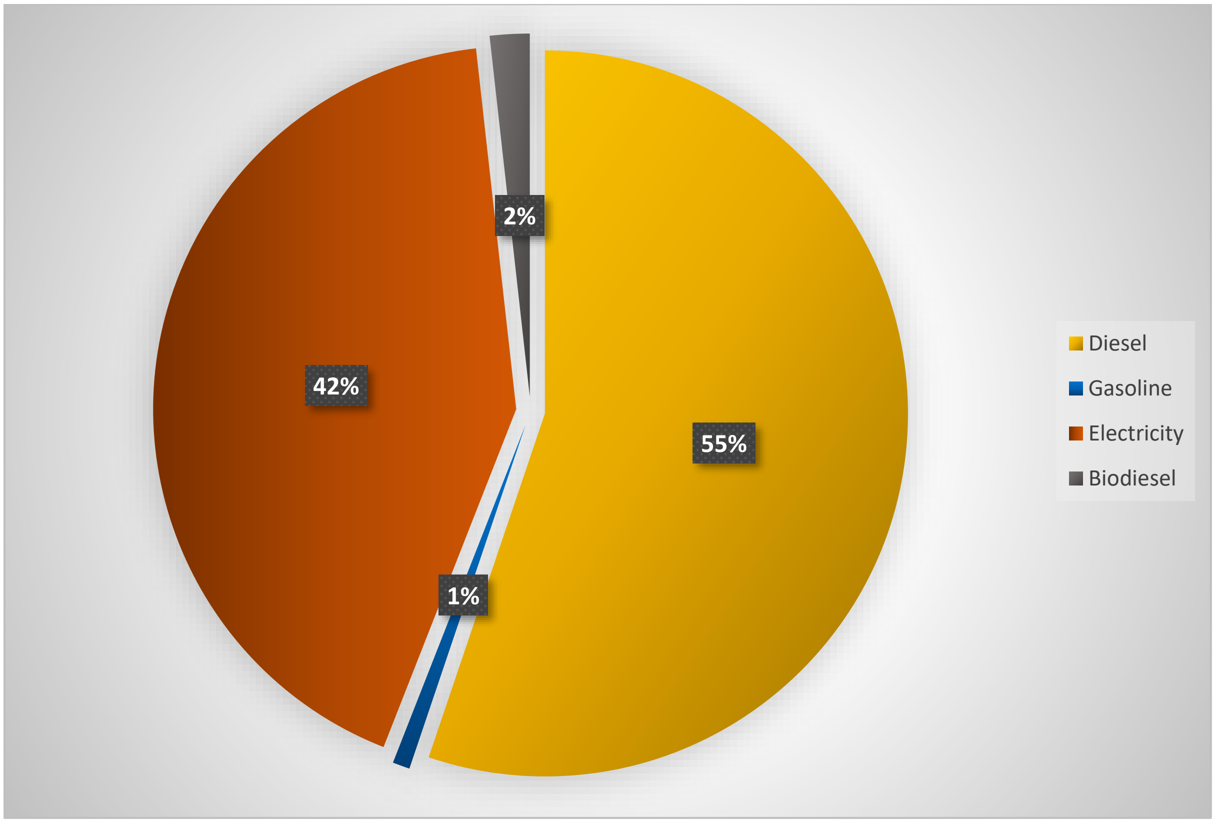

Figure 4-2 Energy consumption from public transportation in Montréal in 2016.

Electricity in Montréal is produced by two main sources: hydropower and thermal power, with ratios of 99% and 1%, respectively (Hydro-Quebec, 2018). Thermal power is described on Hydro-Québec's website as primarily representing gasoline and then, diesel. It is for this reason that, in the present study, electricity is estimated separately with different ratios and emission factors for thermal power (primary gasoline) versus hydropower (Hillman and Ramaswami, 2010) employing an emission factor of 69.3 kg CO_2-eq/GJ (Agência Portuguesa do Ambiente, 2017) for the former and an emission factor of 0 for the latter. In most studies of this nature, it should be noted, the emission factor for hydropower considered for the LCA is 0.025 kg CO_2-eq /kWh while the standard emission factor is 0. Since the present study concentrates on urban GHG emissions and the estimation spans a single year (2016), 0 is the standard emission factor considered here. Ostensibly, the largest share of GHG emissions from electricity is attributable to thermal power. Figure 4-3 shows that in 2016 diesel corresponded to emissions of 138.65 million kg CO_2-eq to the atmosphere, representing the highest GHG emissions among fuels by %95, used in public transportation in Montréal at 95%. Meanwhile, electricity is the second-largest fuel in Montréal as per a 2016 study, representing 42% of total energy consumption. Interestingly, only 993.77 t CO_2-eq in emissions was produced by electricity generated by thermal power, owing to the low rate of electricity generation of this source. Biodiesel and gasoline, with rates of 2% and 1%, respectively, are the other fuels consumed in this sector. Despite the low rate of biodiesel, it is the second-largest driver of GHG emissions in Montréal Island at 3% of total emissions, while gasoline was the second-least significant driver of GHG emissions by the public transportation at 1%.

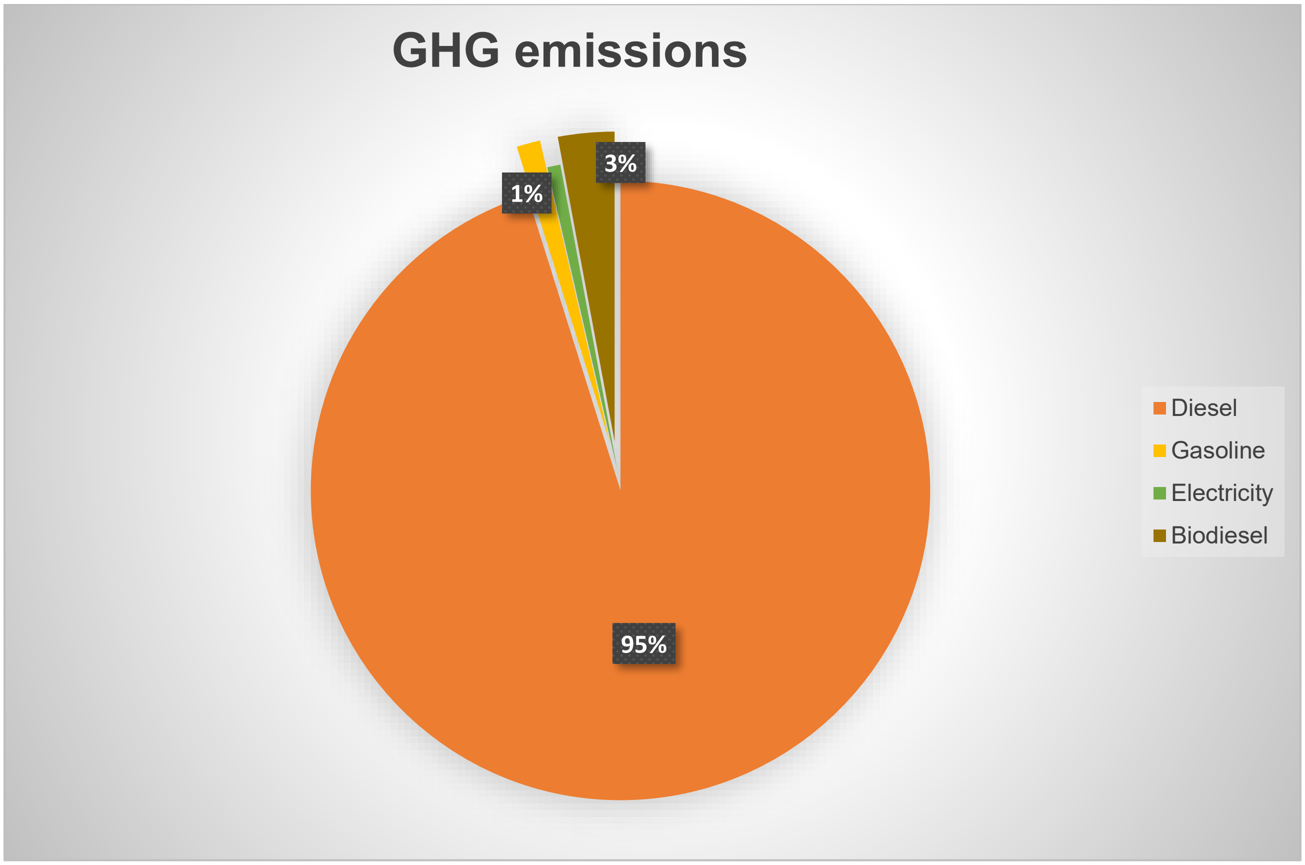

Figure 4-3 GHG emissions from public transportation in Montréal City by sources in 2016.

Figure 4-4 illustrates the GHG emissions by diesel during the period 2006 to 2016, showing a sudden reduction in 2007 and then remaining at that level in 2008. This was followed by an increase from 125 kt CO_2-eq in 2008 to about 135 kt CO_2-eq in 2009, peaking in 2011 at approximately 149 kt CO_2-eq. It had decreased slightly by 2015, while by 2016 it had seen slight growth. It is now anticipated to remain at a constant level, as the Québec government is seeking to encourage the use of hybrid buses.

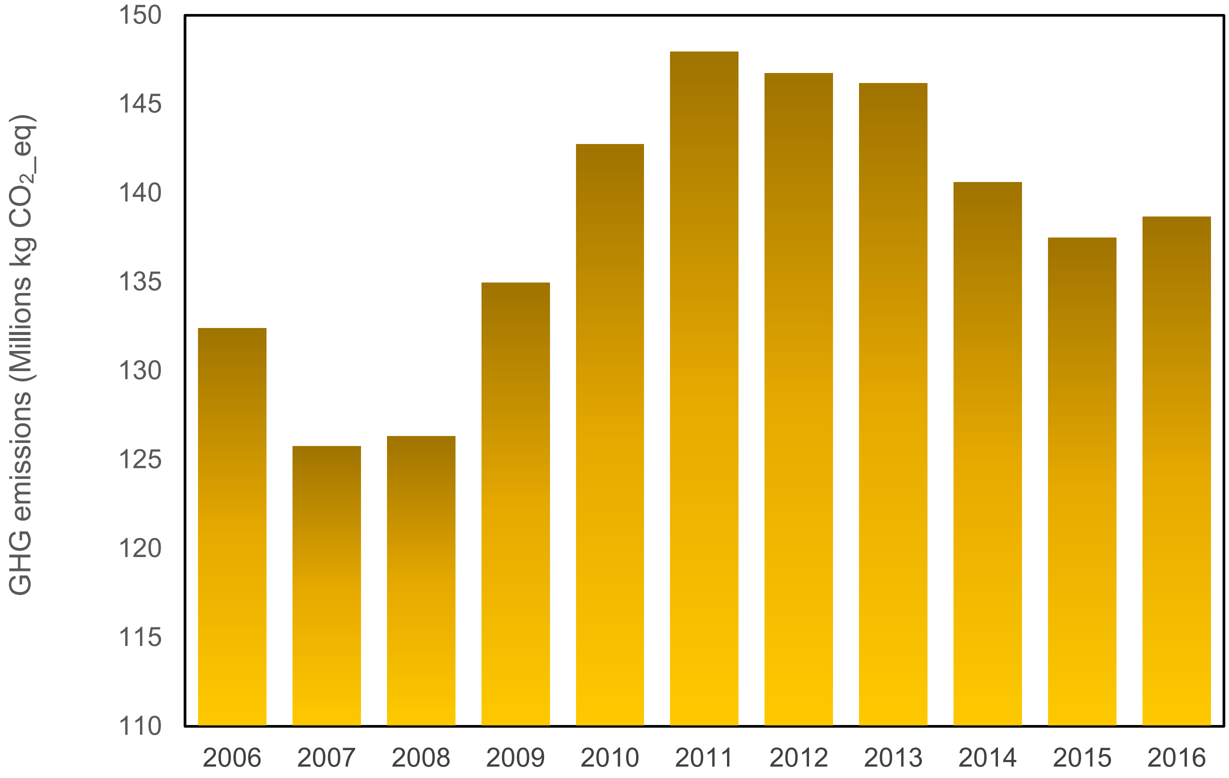

Figure 4-4 GHG emissions from diesel consumptionin public transportation.

As discussed above, electricity is generated by two sources, hydropower and thermal power which present the same trend of consumption over the 10-year period from 2006 to 2016 shown by Figure 4-5, although the GHG emissions produced by these two different sourses are different due to their emission factors. The emission factor for electricity generated by hydropower is zero (Koffi et al., 2017) which makes the GHG emissions by electricity generated by hydropower zero. So that, the GHG emissions produced by this sourse only belongs to electricity generated by thermal power sourses. At the beginning of the period, the trend experienced sudden growth and then continued to rise gradually up to 2014, remaining stable until 2016. Due to the low rate of electricity generation which is only %1, the GHG emissions produced by electricity generated by thermal power are very low, representing emissions of 993.762 kg CO_2-eq, although the amount of CO_2-eq produced by gasoline is high.

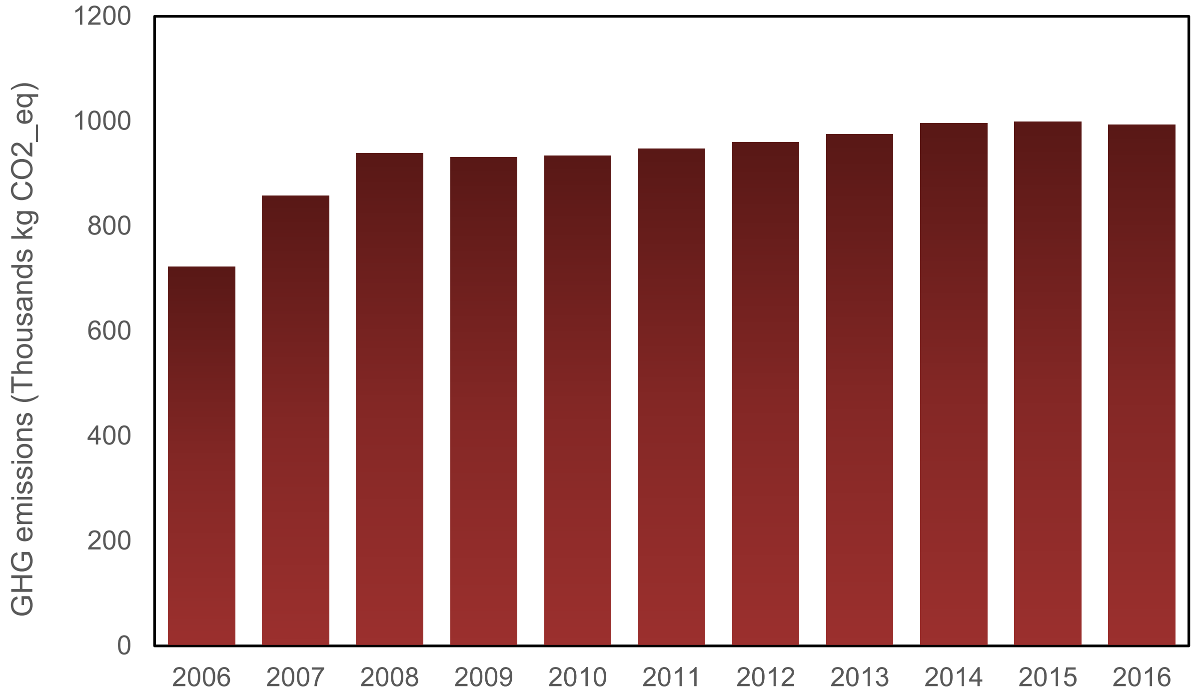

Figure 4-5 GHG emissions from electricity consumption in public transportation.

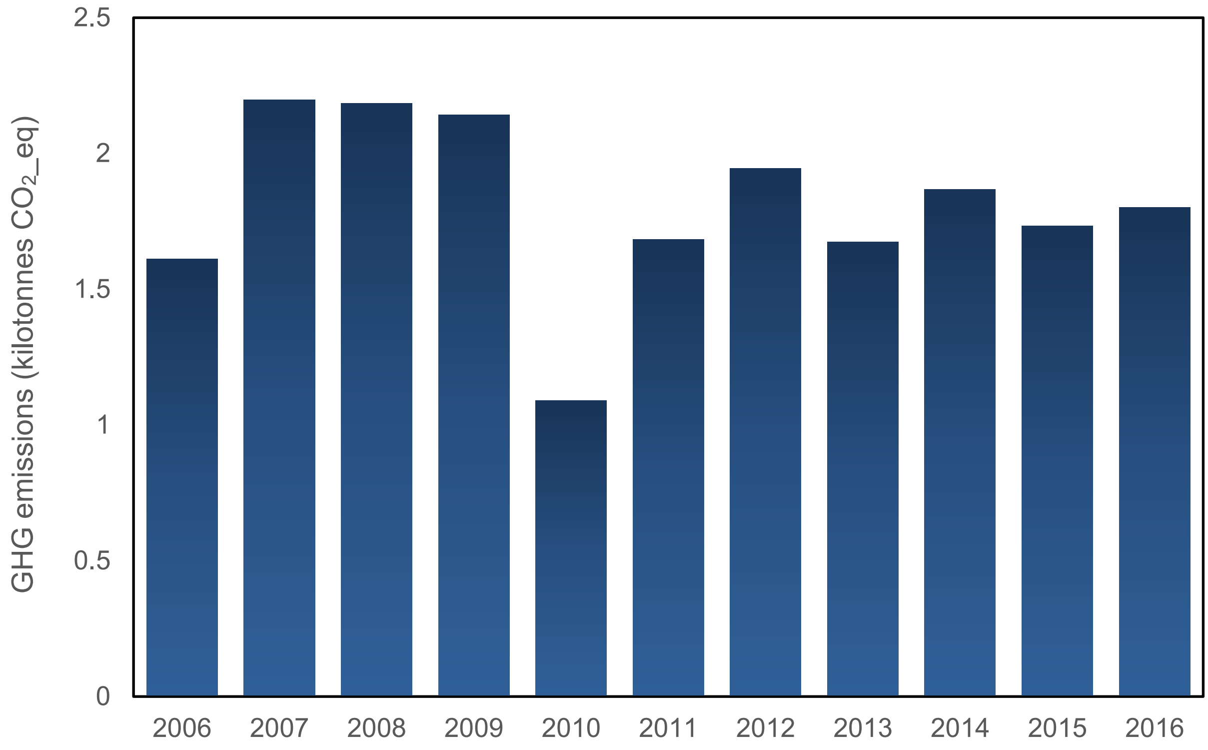

Figure 4-6 GHG emissions from gasoline consumption in public transportation.

The figure below (Figure 4-7) illustrates GHG emission by biodiesel consumption in the urban transportation network. (It should be noted that there is no data for biodiesel in 2006.) As can be seen, biodiesel emissions saw a sudden growth in 2008, had stabilized by 2015, then decreased moderately in 2016, with this increase corresponding to an increase in the use of electricity as a fuel source.

The fuel consumption data is provided in the STM annual reports, although the amount of biodiesel consumption for not specified in the 2006 report. The GHG emissions produced by biodiesel in 2007 was very low, although it had increased to approximately 4 kt CO_2-eq by 2008 and then saw a sudden growth in 2009. It had stabilized by 2011, undergoing some changes between the years 2012 and 2014, and then peaking in 2015 with more than 5 kt CO_2-eq. The figure shows a sudden reduction in 2016, indicative of the efforts of the government to encourage use of hybrid buses.

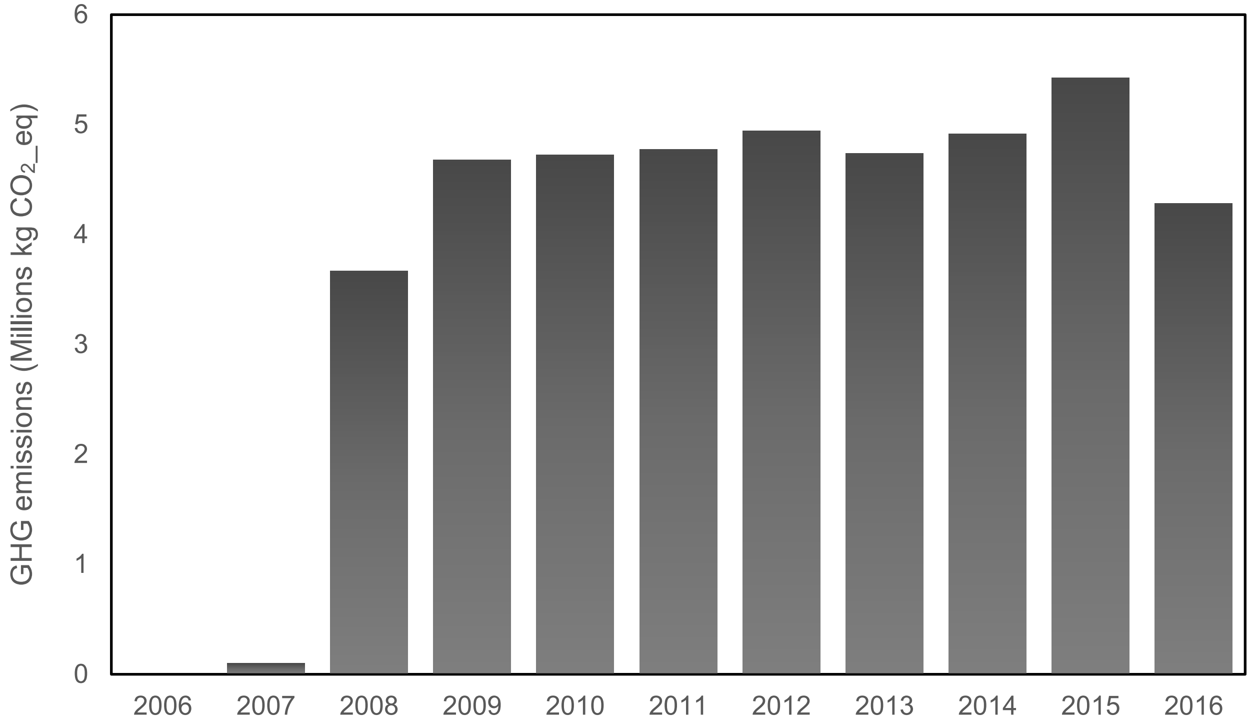

Figure 4-7 GHG emissions from biodiesel consumption in public transportation.

Montreal is committed to reduce GHG emissions by 30% below 1990 levels by 2020 and by 80% by 2050 (Ville de Montréal, 2016). In public transport sector, the efforts have been conducted to reduce dependence on fossil fuels by increasing the traveling by feet and bicycle. In order to meet the goal, they have also planned to convert 30% of the Société de transport de Montréal bus fleet to hybrid engines, convert 230 municipal vehicles of conventional 4-cylinder vehicles to 100% electric power and replacing 100 8-cylinder vans in the municipal fleet to smaller-engine vehicles by 2020. Moreover, they have increased the annual budget devoted to universal access to improve accessibility to urban services and facilities.

4.3. Emissions from Suburban Transportation Network

The Island of Montréal is surrounded by other small islands and cities, resulting in a large population of people commuting to Montréal on a daily basis. RTM refers to the lines that move the passengers by commuter train. In Montréal, there are 6 lines: Exo1-Vaudreuil–Hudson, Exo2-Saint-Jérôme, Exo3-Mont-Saint-Hilaire, Exo4-Candiac, Exo5–Mascouche, and Exo6-Deux-Montagnes. Due to the linking of Montréal proper to the suburbs by these six lines, in the current study, these lines are referred to as the Suburban transportation Network (STN), and the estimation is carried out according to the total distance traveled by these trains within Montréal. Due to the lack of data about the distance traveled by trains, this distance must be obtained by checking the distances on the train maps available on the Exo.québec website (EXO, 2019), then multiplying this by the number of shifts per day and then by 365 days excluding weekends and holidays which no services offer in a year to achieve the total distance traveled by these trains annually. Accordingly, Exo1-Vaudreuil–Hudson is found to have traveled 160,855.5 km, Exo2-Saint-Jérôme to have traveled 142644.19 km, and Exo3, 4, 5, and 6 to have traveled 42,157.5 km, 75193.65 km, 101966.4 km, and 183,806.7 km, respectively. The emission factor for these trains, it should be noted, is 0.0152 kg CO_2-eq /tonne-km (CN, 2020). The average weight of the trains is another factor considered in the calculation. Due to the fact that different trains are driven in each line, after finding the types of trains and their weights, the average train weight is determined for use in the emission calculations. Therefore, the only variable factor is the travel distance in each line, which is why as shown in Figure 4-8, the highest GHG emission belongs to Exo-6, with the longest distance. This line, in particular, was found to have emitted 329.43 t CO_2-eq in 2016, while the total GHG emissions produced by the STN in Montréal in 2016 was 1,266.47 t CO_2-eq. However, the second-largest GHG emitter was Exo 1 (Vaudreuil–Hudson), traveling 160,855.5 km by 288.30 t CO_2-eq . Exo 3 traveled the least distance at 42,157.5 km, in turn accounts for the least GHG emissions at 75.55 t CO_2-eq.

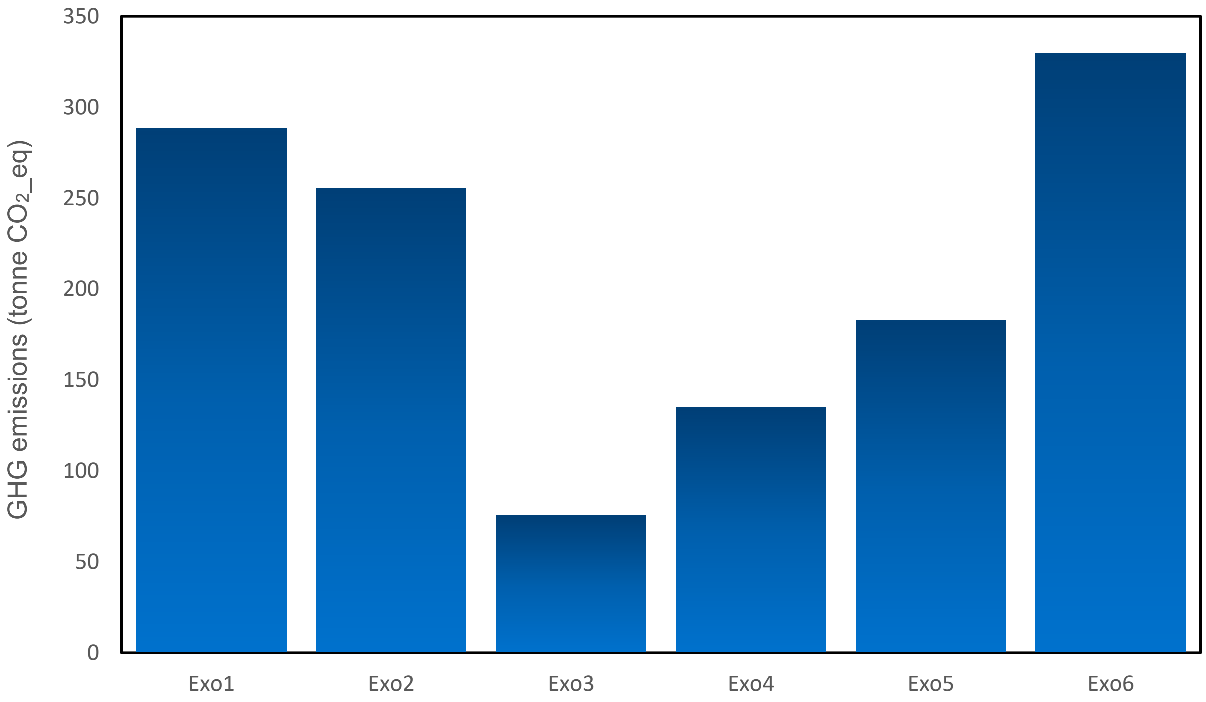

Figure 4-8 GHG emissions from suburban transportation network in 2016.

4.4. Emissions from Vehicles

The methodology typically used for quantifying GHG emissions by the transportation sector is either fuel-based or vehicle-based, where the method employed depends on the activity data available. For the present study, a methodology was developed based on the number of vehicles registered in a given year in the urban area under study. Statistics on registred vehicles were obtained from Société de l'assurance automobile Québec (SAAQ) and Table 4-4 shows the number of vehicles in circulation in Montréal from 2002 to 2016 (Societe de Anssurance Automobile Quebec, 2007, 2008, 2009, 2016). The data was collected during the registration of road vehicles, where the number of vehicles considered to be in circulation corresponds to the number of vehicles whose license plate is current as of December 31 of the given year. The vehicles in storage, decommissioned, or otherwise unregistered before that date, therefore, are not included in the total. In addition, trailers and vehicles used exclusively at railway stations, ports and airports are not considered in the calculation of the number of vehicles in circulation. The vehicles are grouped according to the category of use. These categories are defined in the SAAQ reports as follows:

Personal purpose means that the authorization to circulate was obtained by an individual or more of co-owners, and the use of the vehicle is mainly for personal purposes. **Utilization institutional, professional or commercial purpose** means that the authorization to circulate was obtained by a legal person, a government, a public organization, a society, a company, an agricultural producer, or a professional working on their own. personal purpose is defined by who has not Canadian citizenship and who is a staff member director of the organization of international civil aviation or representative of a member state of this organism, or who is consular officer, a delegate from a foreign country or his assistant. **Off-network** means a vehicle using outside the ordinary road network, either on private land or in a locality not connected to the road network.

Table 4-4 Number of vehicles registered from 2002 to 2016 (Societe de Anssurance Automobile Quebec, 2007, 2008, 2009, 2016)

	2002	2003	2004	2005	2006	2007	2008	2009	2011	2012	2013	2014	2015	2016
Personal purpose Automobile and light truck	634323	648366	653669	655931	7E+05	668059	7E+05	702231	716842	720948	730061	7E+05	747565	760063
Motorcycle	1421	1708	1988	2289	2824	3336	13020	12568	12327	13668	14322	15079	15710	16211
Moped	0						4173	4496	4935	5291	5402	5354	5244	5273
Motor home	0						668	732	692	663	653	626	634	624
UIPCP Automobile or Light truck	120307	125656	128113	131025	1E+05	132275	1E+05	11865	100963	101020	102793	1E+05	105051	106139
Taxi	3541	3527	3489	3470	3399	3347	3313	3289	3306	3265	3260	3273	3234	3212
Bus	2309	2279	2262	2291	2290	2296	2370	2317	2709	2307	2378	2303	2286	2362
School bus	620	655	722	859	861	886	903	733	933	856	1028	1033	1054	1049
Truck or tractor unit	21688	22744	23817	24841	24779	24906	24092	23283	23385	23896	24319	24545	25055	25333
Tool vehicle	7905	8152	8446	8819	8967	9052	5416	5610	5788	5959	6140	6132	6166	6298
Motorcycle, moped,motor home and others	0	0					3526	3566	3719	3887	3906	3818	3949	4098
Restricted circulation	0	0					1119	1502	2063	1017	946	865	806	827
Off network - Snowmobile	4005	4514	4180	4076	3843	3788	3781	3736	3294	3161	3222	3153	3022	2899
Off-grid - all-terrain vehicle	7615	7991	8059	8338	8542	9032	9323	9414	9329	9017	9077	9050	9032	8908
Off-grid - tool vehicle	718	776	815	760	858	998	6450	6751	7769	8019	8055	7854	7951	7876
Off-grid - automobile, light truck, moped, bus, truck or tractor unit and others	6260	6257	6382	6659	6878	7209	1137	1326	1167	1229	1104	1269	1320	1356

As mentioned in chapter 3, this study categorizes vehicles according to their weight: light, medium, or heavy.

- light vehicles weigh less than 4,500 kg (e.g., cars, vans, or light pickups)
- Medium vehicles weigh between 4,500 kg and 9,000 kg (e.g., heavy-duty pickups and medium-size pickups)
- Heavy vehicles weigh more than 9,000 kg (e.g., garbage trucks and tandem dump trucks)

Table 4-5 shows the number of registered vehicles in Montréal Island based on the categorization of the present study. As can be seen in the table, under the definition for medium vehicles there is no number. For this reason, the estimation was limited to light and heavy vehicles. The numbers for registered vehicles are extracted from the annual reports; due to the lack of an annual report for 2010, it should be noted, there is no information for this year.

Table 4-5 Number of registered vehicles based on this study categorized

Types of vehicles	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Light Vehicles	759592	779257	787259	792715	798351	8E+05	831130	7E+05	844847	849759	861343	869938	882193	896447
Heavy vehicles	51120	53368	54683	56643	57018	58167	53472	53170	54374	54444	55323	55339	55886	56081

The methodology developed for private vehicles includes 4 factors: number of vehicles registered in a given year, average travel distance by each type of vehicle, fuel economy of each type of vehicle, obtained from the Transport Canada website (Transport Canada, 2019), and emission factor for each type of vehicle. The emission factors based on the different types of vehicles, sources, units, and locations are provided in Table 4-6.

Table 4-6 Road transportation emission factors

Vehicle	**Fuel**	**Emission factor (kg CO_2-eq /unit)**	**Unit**	**Location**	**Reference**
Light vehicle	Gasoline	2.20	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
	Diesel	74.07		Portugal	(Agência Portuguesa do Ambiente, 2017)
		2.58	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
		2.671	Liter	Australia	(Australian Transport Assessment and Planning (ATAP), 2016)
	Natural gas	2.73	kg	BC, Canada	
		1.561	Liter	Australia	(Australian Transport Assessment and Planning (ATAP), 2016)
	Electricity	0.010	kWh	BC, Canada	(Ministry of Environment British Columbia, 2016)
Medium Vehicle	Gasoline	2.20	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
	Diesel	2.58	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
		2.671	Liter	Australia	(Australian Transport Assessment and Planning (ATAP), 2016)
	Natural gas	2.73	kg	BC, Canada	(Ministry of Environment British Columbia, 2016)
Heavy vehicle	Gasoline	2.20	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
	Diesel	74.07		Portugal	(Agência Portuguesa do Ambiente, 2017)
		2.58	Liter	BC, Canada	(Ministry of Environment British Columbia, 2016)
		2.671	Liter	Australia	(Australian Transport Assessment and Planning (ATAP), 2016)
	Natural gas	2.73	kg	BC, Canada	(Ministry of Environment British Columbia, 2016)

Figure 4-9 Shows the GHG emissions from private vehicles over the period of 2002 to 2016. GHG emissions produced by heavy vehicles in Montreal are greater than GHG emissions from light vehicles, but this big difference can be attributed to the average distance traveled by these types of vehicles. Owing to the lack of data the average travele distance employed to calculate the GHG emissions, belongs to Quebec and due to the great numbers of highways in Quebec this factor is bigger than the average travel distance by light vehicles.

At the beginning of the period between 2002 to 2007 the trend was seen a growth, althought this increase for light vehicles is not as significant as heavy vehicles. GHG emissions reached to its peak by 2007 with 4173.47 kt CO_2-eq. There is a sudden reduction for both trends light and heavy vehicles but for light vehicles happened in 2009 and for heavy vehicles occurred in 2008, and then they are followed by a slight raise by 2016, reachin 2, 889.64 kt CO_2-eq by light vehicles, representing the highest GHG emissions over 13-year period and 4, 023.8 kt CO_2-eq by heavy vehicles.

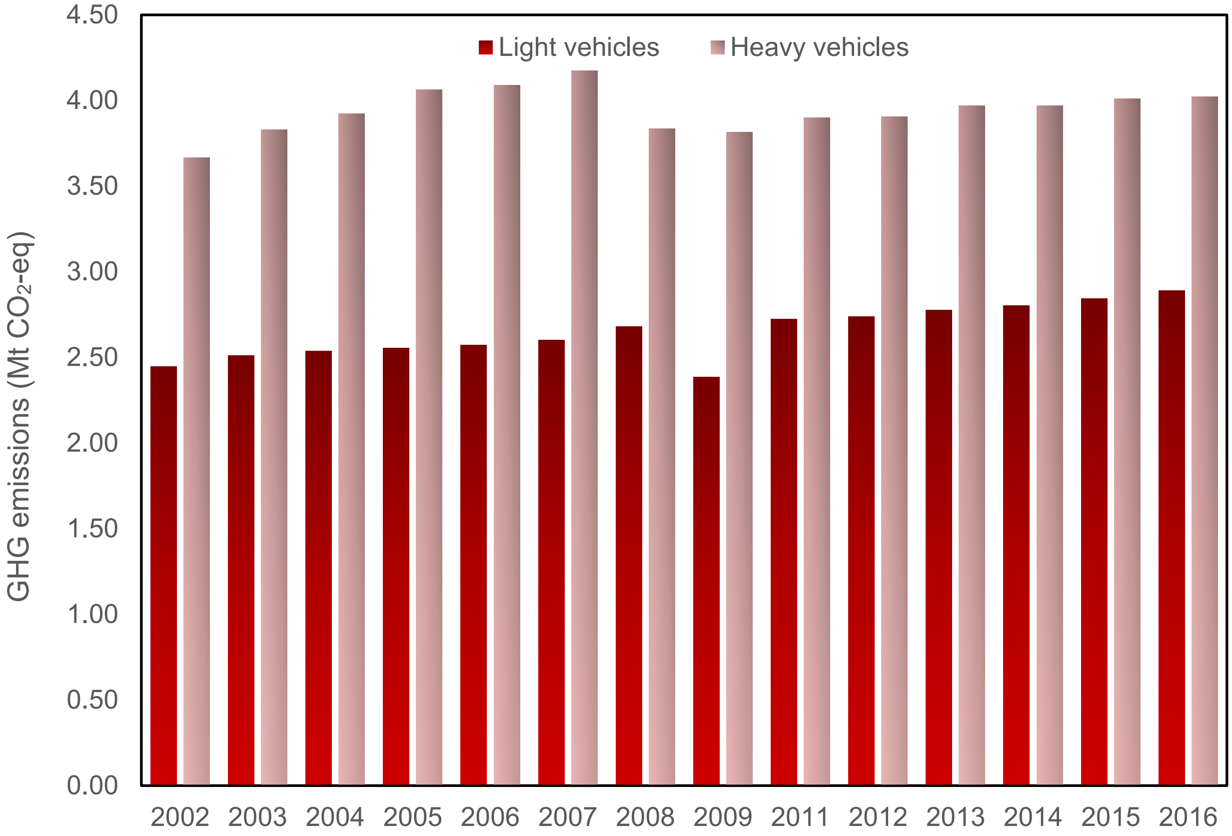

Figure 4-9 GHG emisisons from vehicles

The city has plans to reduce GHG emissions from private vehicles, which is one of the most significant contributor with a considerable amount of GHG emissions annually. Due to increasing number of private vehicles every year, the primary action plan which can help to reduce GHG emission produced by private vehicles is to encourage people to use more public transportation. The city has invested on improving public transportation since 2013 (Ville de Montréal, 2018). The city has encouraged employees by establishing measures like financial incentives, replacing car expense allowances with transit passes or memberships in collective and active transportation services. In addition, increasing the number of fuel-efficient vehicles like electric cars is another action plan which has been developing by installation of 1,000 on-street electric charging stations across the city by 2020 and establish a regulatory framework to allow deployment of 1,000 car-sharing electric vehicles (Ville de Montréal, 2016).

4.5. Emissions from Fuel-based Heating

Historically, Québec has been a consumer of western Canadian natural gas. More recently, growing gas production in the U.S., a reversal of export points in Ontario, and additional interconnections between Ontario and Québec have enabled higher rates of delivery of U.S. gas into Québec.

Energir (Gaz Métro) distributes gas to approximately 300 municipalities via over 10,000 km of pipelines. Enbridge Gazifère operates 932 km of pipelines and serves the Outaouais region. Energir (Gas Métro) and Gazifère are provincially regulated by the Régie de l'énergie (Energir, 2019). The three main GHGs produced from the combustion of natural gas are CO_2, CH_4, and N_2O. The method that has been developed to estimate GHG emissions from fuel-based heating includes total fuel consumption multiplied by emission factors for each source of fuel. Most heating in Montréal, it should be noted, is provided by natural gas, while some is provided by heating oil and electricity. GHG emissions from fuel-based heating are estimated in the present study by considering two sources, natural gas, and heating oil, while electricity has been studied in another sector which is only belonged to this area. The emissions factors for natural gas based on different units and locations are provided in Table 4-7. The emission factor which this study has considered for natural gas is 1.888 kg CO_2-eq /m^3 (Government of Canada, 2017b). This factor is chosen for two reasons: this emission factor was developed for Québec which is the province of the case study of the present study, and its unit matches the activity data.

The activity data of natural gas consumption was provided by Energir, and these data is not published for the public. The reported natural gas consumption is categorized by four sectors, residential, commercial, industrial and institutional, as shown in Table 4-8. The natural gas consumption for industry part reported by Energir here only belongs to small industries as mentioned before that large industries in Montréal are not required to report their GHG emissions.

Figure 4-10 illustrates natural gas consumption in Montréal, where industry at 39% is shown to consume the highest rate of natural gas in Montréal, followed by commercial with 25%, while institutional and residential are the lowest and second-lowest consumers of natural gas in Montréal, with 22% and 14% respectively.

Table 4-7 Emission factors for natural gas

Location	**Emission factor(kg CO_2-eq per unit)**	**Unit**	**Reference**
	53.6	Scf	(U.S. EPA, 2018)
Canada	56	GJ	(Government of Canada, 2017b)
	56.11	GJ	(Government of Canada, 2017b)
The Netherlands	63.1	GJ	(SenterNovem, 2005)
British Columbia, Canada	49.58	GJ	(Ministry of Environment British Columbia, 2016)
Quebec	1.887	M^3	(Government of Canada, 2017b)
Ontario	1.888	M^3	(Government of Canada, 2017b)
British Columbia	1.926	M^3	(Ministry of Environment British Columbia, 2016)
	0.05444	Scf	(U.S. EPA, 2018)
New York	50.411	GJ	(The City of New York, 2017)

Table 4-8 Natural gas consumption in the Montréal Island (Energir, 2019)

Sector	**2013-2014 (M^3)**	**2014-2015 (M^3)**	**2015-2016 (M^3)**	**2016-2017 (M^3)**	**2017-2018 (M^3)**
Commercial	477.3	482.8	475.47	445.951111	446.7

Industrial	674.5	659.6	690.10	762.438347	848.6
Institutional	263.7	260.7	258.59	263.179179	255.3
Residential	397.2	392.2	398.14	413.19985	407.6
Total	1,812.6	1,795.3	1822.3	1884.8	1,958.2

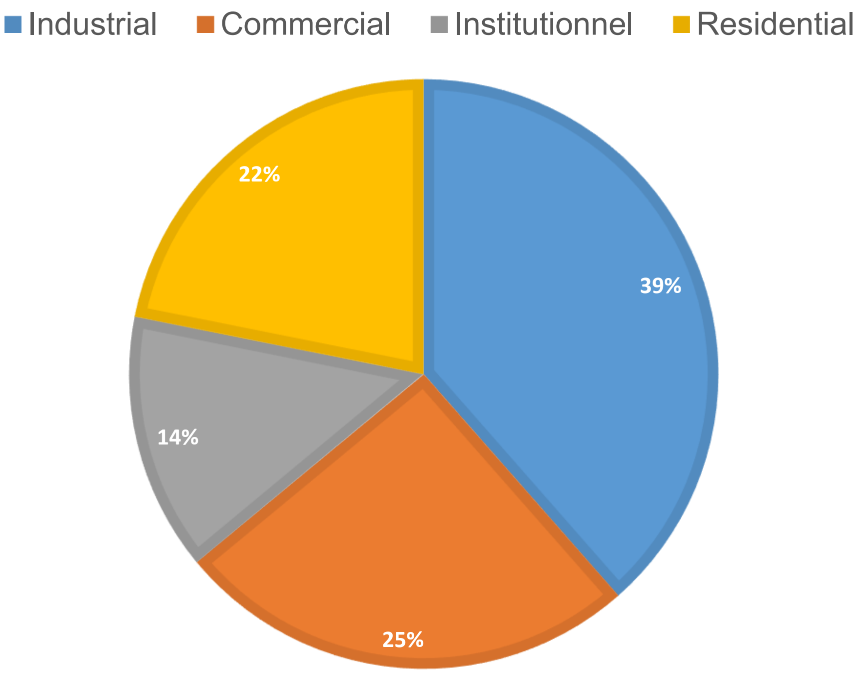

Figure 4-10 Natural gas distribution in Montréal by sector in 2016.

Figure 4-11 shows the trend of GHG emission in Montréal by sector resulting from the use of natural gas during the period 2014 to 2017. Emissions by industry increased moderately by 2017, while GHG emissions by the commercial sector decreased slightly over the same period. GHG emissions by natural gas, meanwhile, experienced negligible growth by 2017, while Energir reported that in 2017-2018 nearly 12.7 million m^3 of natural gas was saved by customers in Montréal by energy-efficiency programs.

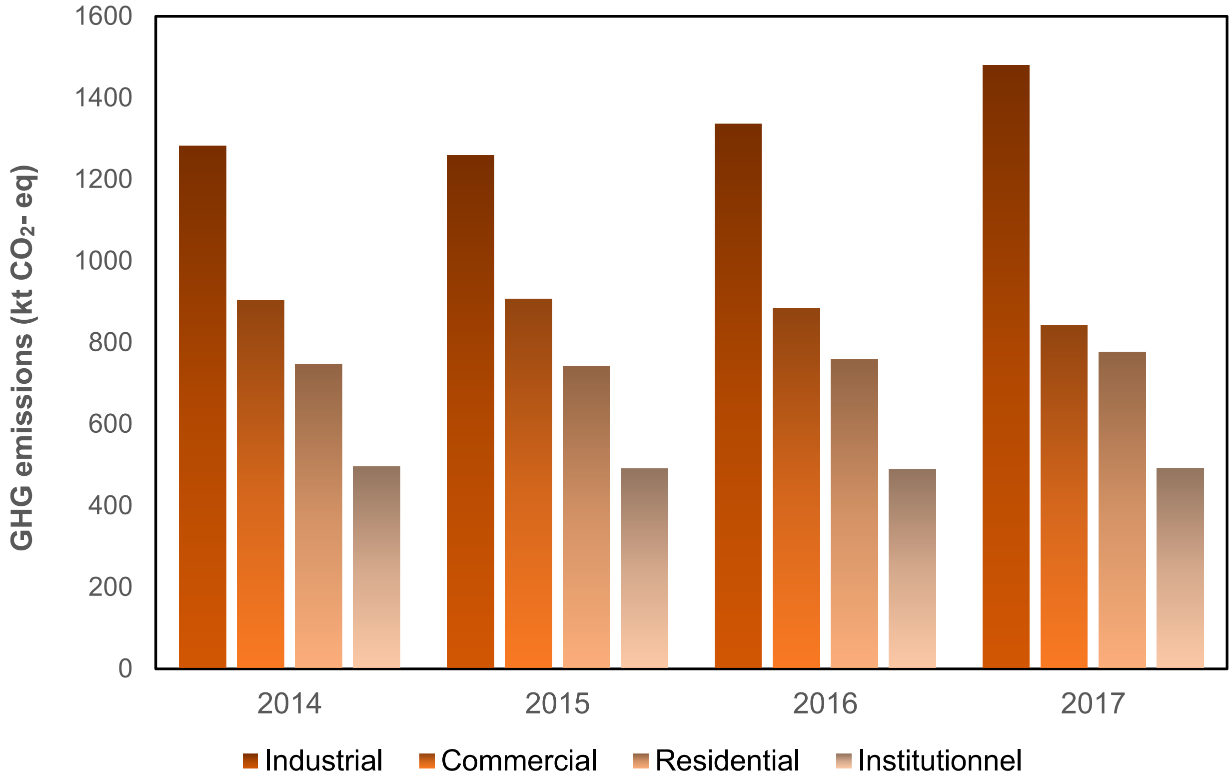

Figure 4-11 GHG emisisons from natural gas-based heating during 2014 to 2017.

In a comparison of Montréal with New York City and London illustrated in Figure 4-12, Montréal is found to have produced the lowest GHG emissions in 2016. The highest GHG emissions belonged to New York City with about 15,000 kt CO_2-eq. Despite the fact that New York City and London are similar in population, gas consumption in New York City is approximately 3 times greater than in London. This is due to the energy-efficiency improvements that have been implemented in London, including increased levels of insulation, new boilers, and more energy-efficient appliances; increased prices and the recession; and changes in the building stock and household composition. The largest source of GHG emissions in New York City is found to be the combustion of natural gas in buildings, whereas, in Montréal, the highest GHG emissions driver from natural gas consumption is the industrial sector.

In comparison of these cities per capita (Figure 4-12) illustrates the role of individual residents in shaping GHG emission trends. As shown in the figure, although Montréal Island emitted the least total GHGs in 2016 among the cities, per capita GHG emissions were higher than in the other cities. New York City had the second-highest per capita GHG emissions in this comparison, even though it was the largest GHG emitter in total.

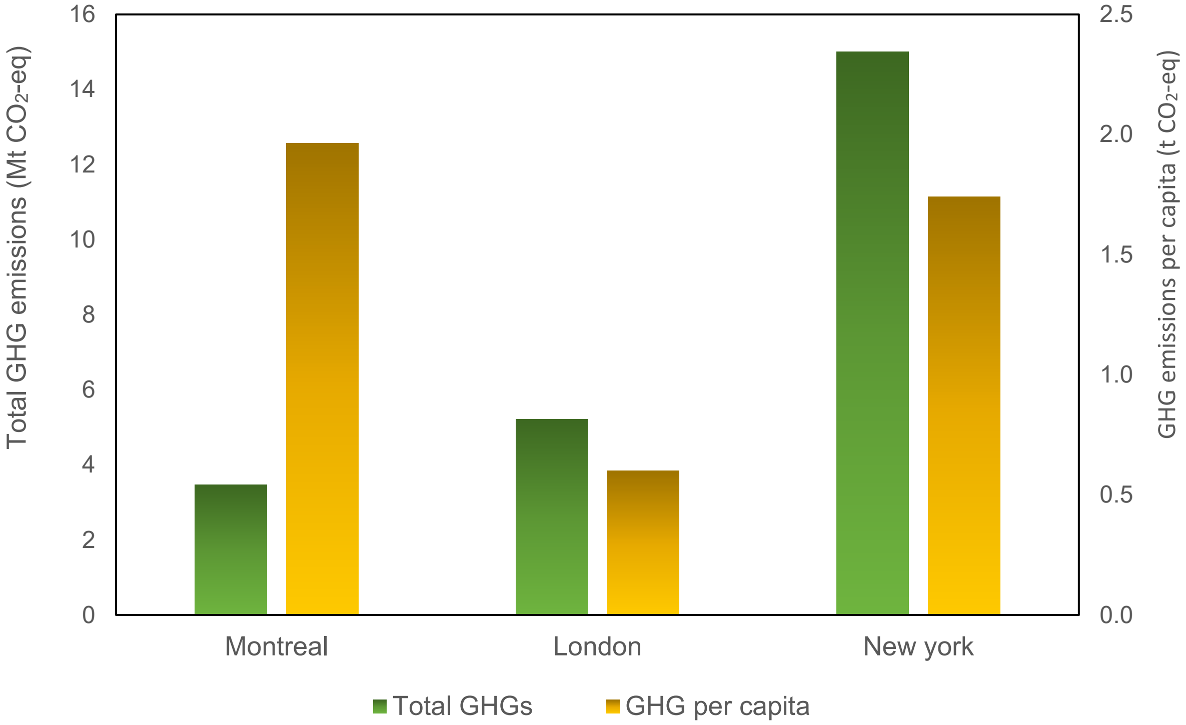

Figure 4-12 GHG emissions from natural gas consumption in different cities in 2016.

Oil is another source of heating in Montréal whose GHG emissions are estimated, employing a linear relation to multiply the total oil consumption by an emission factor. The Québec government, it should be noted, is seeking to reduce the use of thermal coal and reduce by 40% the number of oil products used in the province. The Québec government is also seeking to improve the efficiency of each source of energy by 15%. In order to meet these goals, Québec will assist households and industries to reduce energy consumption. Among the energy-efficiency initiatives, building codes will be modified and energy-efficient renovations encouraged. The Québec government will also encourage the use of Québec-sourced energy, including hydro, wind, biomass, and geothermal. Households will receive credits for achieving self-sufficient energy production by wind and solar. Moreover, the Québec government aims to increase the use of renewable energy by 25%, including 50% more biomass energy. A new hydrocarbon law is planned, and revenues generated from natural gas and oil production will be used to support further decarbonization (Flèche, 2016).

There is a lack of available data on oil consumption for heating in Montréal. CTV News (CTV Montreal, 2019) reported on the Montréal mayor's talks about heating oil in which she mentioned that the use of heating oil has decreased slightly over the years, but some 25,000 households still use it. Another 23,000 households use a dual-energy system. Since 23,000 households are using dual-energy, half of this number is considered and then added to the 25,000 households using oil. As such, it is considered that 36,500 households in Montréal are consuming oil for heating and, given that a typical home in a mild climate uses between 5,000 kWh and 30,000 kWh of energy per year for heating (OVOenergy), the average is assumed, and this corresponds to 90 GJ. The oil consumed for meeting heating demand in Montréal is primarily gasoline, so the emission factor considered is 69.3 kg CO_2-eq /GJ, meaning that the GHG emissions produced by heating oil is 227,650.5 t CO_2-eq.

Due to high contribution of heating to GHG emissions, Montréal is setting action plans to reduce GHG emissions from this sector. Canada government has set up the goal to reduce GHG emissions from oil and natural by 40 to 45 percent by 2025 and use renewable enery for heating (Government of Canada, 2019). Montréal has set the goal for achieving building sustainability. To meet the requirement, recognized certifications should be targeted. Improving energy efficiency and eliminating heating oil as energy source should also be impletmented. To meet this goal, the action plans have been taken including reducing energy consumption in municipal buildings by 5% (around 1 MGJ/year) by 2020, eliminating heating oil by 2020 for the city, and ensuring that 75% of new business-support subsidy programs for building construction, expansion and renovation meet ecological criteria. The city also aims to certify LEED which is used for reducing building contribution to climate change and make municipal buildings more resource-efficient and sustainable (Canada Green Building Council, 2020).

4.6. Emissions from Electricity-related Activities

Hydroelectric power is the main source of energy used by Hydro-Québec to produce electricity, which is why very little fossil fuel is used for generating electricity in Montréal compared with other jurisdictions (Hydro-Quebec, 2017). Hydro is the source of 99% of the electricity in Montréal, provided by 63 hydroelectric generating stations, while the remaining 1% is generated by thermal power stations operating continuously to meet baseload energy needs (for instance, diesel generating stations), as well as some gas-fired facilities operating only when demand is high and hydroelectric facilities are working at maximum capacity (Hydro-Quebec, 2017).

Data pertaining to the amount of electricity used is obtained from annual reports published by Hydro-Québec. Because Hydro-Québec’s electricity is produced on an integrated network for the whole of Québec, though, the data in these reports does not specify the electricity demand for Montréal in particular. For instance, the electricity consumed by customers comes from the overall network of Hydro-Québec, not from a specific power plant or interconnection. Hydro-Québec's transmission and distribution grid lines are interconnected and reach all customers over Québec, with the exception of the off-grid generating stations (Hydro-Quebec, 2019). Therefore, in order to estimate GHGs in Montréal, electricity consumption is assessed as a proportion of the Québec population. The population of Québec in 2016 was 8,164,361, while the population of Montréal proper was 1,765,616 (Statistics Canada, 2016)

According to Hydro-Québec annual reports, electricity consumption in Québec is categorized into three sectors: residential, large industries, and commercial including institutional and small industries,. One of the primary GHG drivers in Québec is large industry, although, as per the reasons given in section 4.1, the large industry does not play a noticeable role in GHG emissions production in Montréal, and small industries are already considered in the commercial category. For these reasons, the large industry is not considered in this sector. Table 4-9 is extracted from HydroQuebec annual report (Hydro-Quebec, 2016) which represents the electricity consumption in Quebec and electricity consumption by Montréal in 2016.

Table 4-9 Total electricity consumption in Quebec in 2016 by categories (Hydro-Quebec, 2016)

Segment	Electricity consumption in Quebec (GWh)	Electricity consumption in Montréal (GWh)
Residential	65,065	14,070.88
Commercial, institutional and small industrial	45,483	9,836.10

To calculate the amount of GHG emissions produced by electricity consumption in Montréal, the above amount is multiplied by the population of Montréal and then divided by the population of Québec. Table 4-10 clarifies the electricity consumption in Montréal from 2006 to 2016 to establish a trend of GHG emissions by electricity consumption over the period under study. The emission factors also collected from different sources are shown in Table 4-11, Table 4-12 and Table 4-13.

Table 4-10 Total electricity consumed in Montréal (GWh) (Hydro-Quebec, 2012, 2014)

Year	**Sector**	**Total Electricity Consumption in Quebec (GWh)**
	Residential	14,070.88
2016	Commercial	98,36.10
	Residential	14,393.76
2015	Commercial	9,804.10
	Residential	14,721.61
2014	Commercial	9,772.52
	Residential	14,269.41
2013	Commercial	9,649.47
	Residential	13,479.20
2012	Commercial	7,349.13
	Residential	13,569.82
2011	Commercial	7,259.60
	Residential	12,874.76
2010	Commercial	7,323.61
	Residential	13,512.72
2009	Commercial	7,385.46
	Residential	13,137.08
2008	Commercial	7,618.37
	Residential	12,985.48
2007	Commercial	7,515.21
	Residential	12,266.64
2006	Commercial	7,015.44

Table 4-11 Emissions factors for electricity consumption by place (Koffi et al., 2017)

Location	Emission factor (kg CO_2-eq /GJ)
Austria	86.11
Belgium	111.66
Germany	196.11
Denmark	211.11
Spain	177.5
Finland	116.11
France	40.55
United Kingdom	182.77
Greece	324.16
Ireland	241.66
Italy	196.66
Netherlands	198.88
Portugal	208.33
Sweden	21.94
Bulgaria	251.66
Cyprus	283.05
Czech Republic	222.77
Estonia	442.5
Hungary	188.33
Lithuania	48.33
Latvia	156.38
Poland	329.16
Romania	301.11
Slovenia	167.22
Slovakia	98.05
China	0.23-0.28
Russia	175.55

The calculation is carried out based on emission factors and ratio of electricity generation. Table 4-12 shows the emission factors for the operation of each source, while Table 4-13 gives the emission factors for life cycle assessment (LCA) of the sources. Since the present study is evaluating municipal GHG emissions for a single year (2016), only the emission factors for operation are considered in the calculation. It should also be noted that the emission factors are collected from different sources with different units. As shown in Table 4-12, the emission factor for operation in electricity generated by hydropower is 0. As mentioned above, in Québec 99% of electricity is generated by hydropower and just 1% is generated by diesel- and gasoline-fired thermal power plants. The emission factor for electricity generated by thermal power is considered the middle number of oil-fired plants. Therefore, the total GHG production in Montréal in 2016 by electricity is calculated 202.014 kt CO_2-eq.

Table 4-12 Emission factors for electricity operation

Fuel type	**Emission factor for operation (kg CO_2-eq /unit)**	**Unit**	**Location**	**Reference**
Hydroelectric	0.376	m^3	Japan	(Shimizu, Y and others, 2012)
	0	MWh		(Koffi et al., 2017)

Table 4-13 Emission factor for electricity (Life cycle assessment)

Fuel type	**LCA Emission factor (kg CO_2-eq /unit)**	**Unit**	**Location**	**Reference**
Hydroelectric	0.002-0.048	KWh		(Zhang et al., 2007)
	0.015	KWh	India	(Prakash and Bhat, 2012)
Oil-fired power plant	790-900	MWh		(William Steinhurst and Schultz, 2012)

Figure 4-13 shows the GHG emissions due to electricity generation by thermal power for both residential and commercial use. The GHG emissions produced by commercial is, overall, less than GHG emissions by residential towing to the more usage by this category. It stood at 60 kt CO_2-eq in 2006, although GHG emissions produced in the residential sector is approximately 100 kt CO_2-eq. GHG emissions by commercial are found to have increased slightly by 2008, even though a reduction of about 4 kt CO_2-eq is seen by 2011, and the trend holding in 2012. Sudden growth is then seen in 2013, peaking at 80 kt CO_2-eq and then remaining stable for the remainder of the period under study. This category is found to have emitted 59.28 kt CO_2-eq in 2016. The GHG emissions produced by the residential user category have seen a more stable trend compared to commercial, rising slightly by 2009 to approximately 120 kt CO_2-eq, then decreasing by 2010 to 105 kt CO_2-eq. The trend is found to have risen to 110 kt CO_2-eq by 2011, remaining at the same level in 2012. Peaking in 2013 at 125 kt CO_2-eq, GHG emissions in this category had decreased slightly by the end of the period under study. The electricity consumed by the residential category is found to have been associated with 103.65 kt CO_2-eq emissions from thermal power generation. The calculation carried out, it should be noted, is based on three factors: total electricity consumption, electricity generation ratio, and emission factor. The emission factor and the generation ratio (0.01 for thermal power) are constant values in this method and only the electricity consumption varies. Moreover, the GHG emissions produced by electricity generated from hydropower is 0, given that the corresponding emission factor is 0.

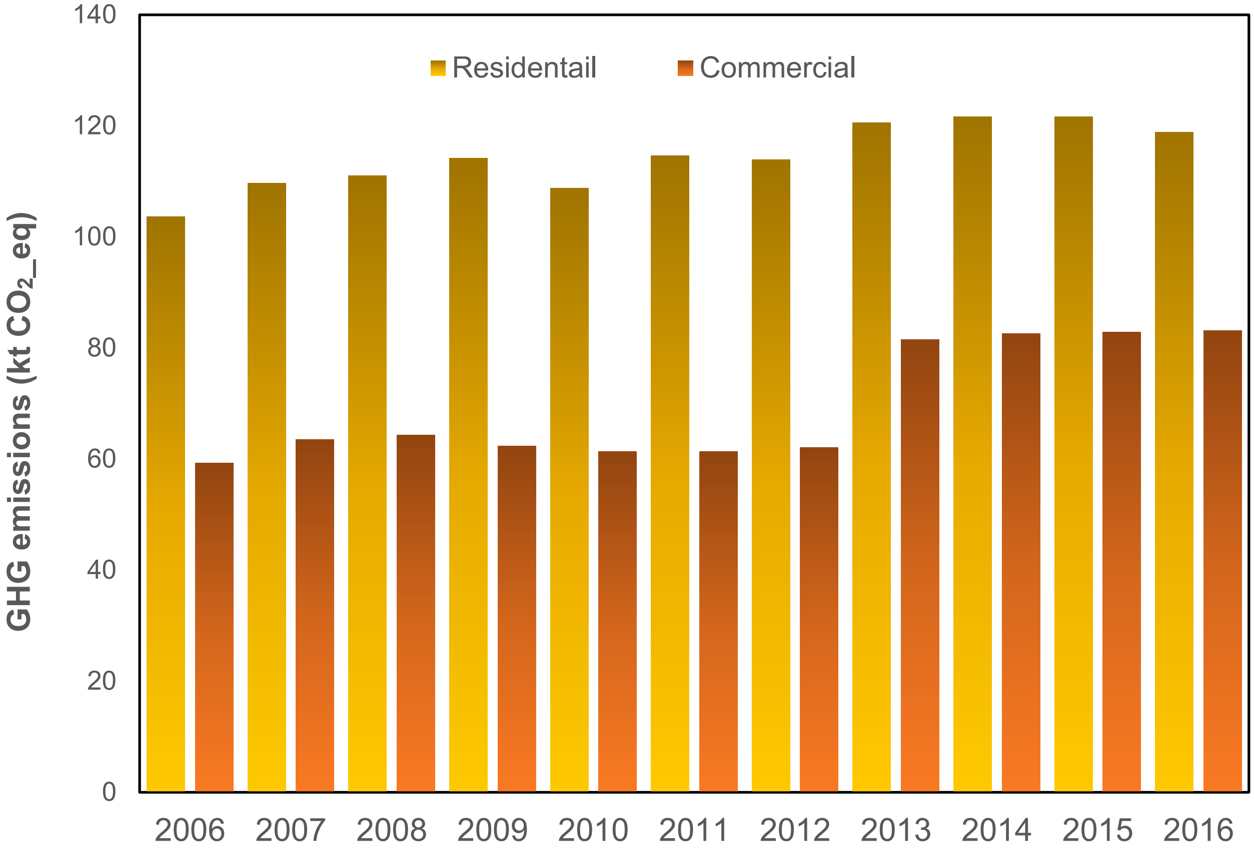

Figure 4-13 GHG emissions from thermal power-based electricity production.

4.7. Emissions from Solid Waste Disposal

In recent years, Montréal has experienced a considerable increase in recovered materials, except for organic matter. In 2008, the rate of recovery of recyclables was 53%. The rate was 54% for hazardous household waste and 43% for construction, renovation, and demolition (CRD) waste and bulky refuse. However, for organic matter, the recovery rate was only 8%, while the overall recovery rate for Montréal was 31%

Anaerobic decomposition of MSW in landfills generates about 60% CH_4 and 40% CO_2, together with other trace gases (Jha et al., 2008). Residential waste includes organics, , leaf, and yard, municipal hazardous or special waste, other recyclable materials such as wood, metal, and tires, as well as construction and demolition materials.

Data about the amount of waste collected in Montréal is obtained from the Government of Québec and is provided in three categories: household waste, industrial, commercial, and institutional waste, and CRD waste. The amount of municipal solid waste for Montréal is shown in Table 4-14. It should be noted that, for the estimation of GHG emissions, CRD is not included.

Table 4-14 Solid waste disposal in Montréal by region (Environment Quebec, 2018)

Region	**Household waste (tonne)**	**Industrial, Commercial and Institutional (ICI)**	**Construction, Renovation, and Demolition (CRD)**
Ville de Montréal-Est	1539	3840	6
Ville de Montréal	437607	546104	89146
Ville de Westmount	4749	533	53
Ville de Montréal-Ouest	1297	3006	5
Ville de Côte-Saint-Luc	7962	2871	22
Ville de Hampstead	1886	28	153
Ville de Mont-Royal	5107	3973	219
Ville de Dorval	4400	14130	1839
Ville de Pointe-Claire	5725	7366	607
Ville de Kirkland	4230	2549	890
Ville de Beaconsfield	3574	609	735
Ville de Baie-D'Urfé	1189	5777	691
Ville de Sainte-Anne-de-Bellevue	1300	970	285
Village de Senneville	219	479	231
Ville de Dollard-des-Ormeaux	13355	6870	838
Montréal Island total	494 138	599 102	95 721

The formula is followed by CH_4 correction factor which, based on other studies, is assumed to be 0.6, while the degradable organic carbon in waste is assumed to be 0.15 kg of carbon per kg of waste. The fraction of DOC dissimilated, meanwhile, is 0.77, while the fraction of CH_4 in landfill gas is assumed to be 0.5. The default amount for recovered methane is 0 due to the lack of CH_4 recovery. Another factor considered is the conversion of C to CH_4, which is 16/12. according to some studies (Gurjar et al., 2004), the oxidation factor has been considered to be zero. The methane generation which is calculated by the developed methodology should be multiplied by the global warming potential for methane is 25. So, the estimation shows that 1, 262.38 kt CO_2-eq was produced by this sector in 2016 in Montréal.

Figure 4-14 shows the comparison of GHG emissions from solid waste disposal in Montréal, New York City, Vancouver, and Regina. In comparison to other cities, the amount of GHG emissions produced in Montréal is higher than that of Regina, which produced 7,056 t CO_2-eq in 2016, although it is less than New York City (with a population of 8.615 million in 2016, having 2,021,979 t CO_2-eq, i.e., the highest emission among these cities), it also should be mentioned that the scale of these two cities is different, with Montréal being much more populous than Regina and more comparable in scale to cities such as Vancouver and New York City. In a comparison of the same cities on a per capita basis. As can be seen in Figure 4-14, although the total GHG emissions produced in Regina in 2016 are less than that in Montréal, the trend based on per capita is more than in Montréal, meaning that Montréalers produced the least GHG emissions among the cities compared.

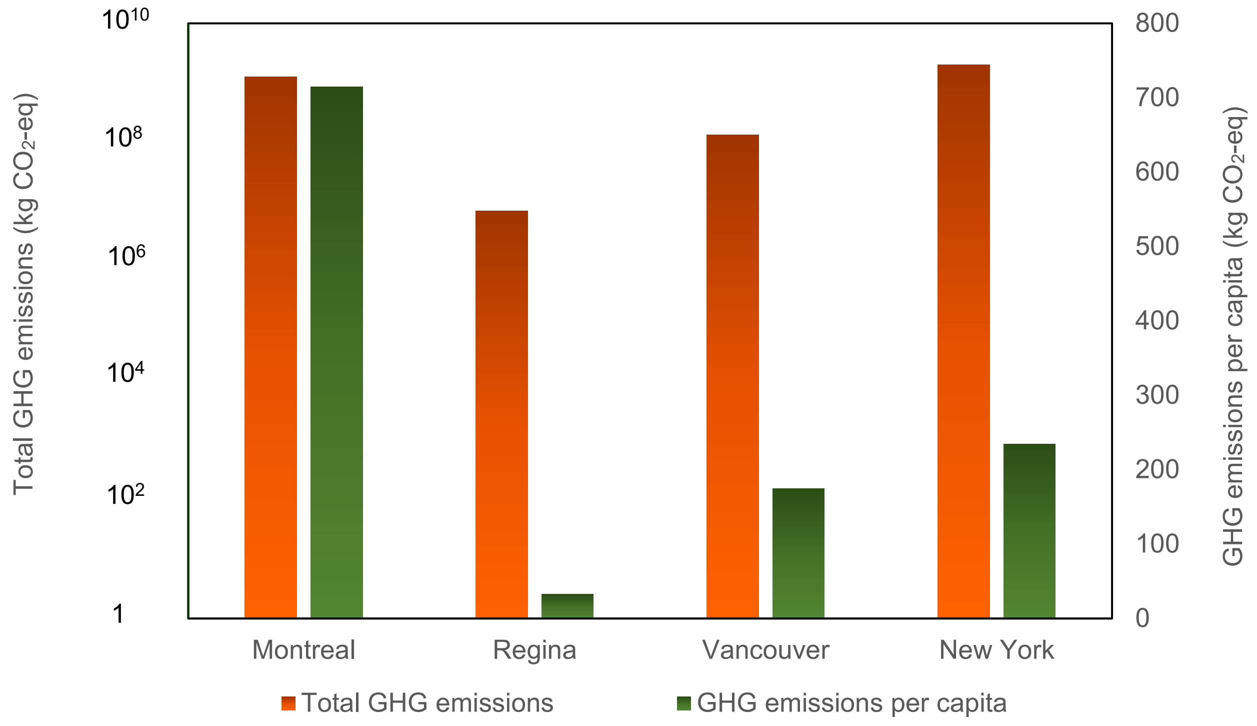

Figure 4-14 GHG emissions from solid waste disposal in different cities in 2016.

To reduce GHG emissions from waste disposal, the city has intended to improve waste recovery with the objectives for recycling 58.3% of recyclable materials by 2014 and 70% by 2020, and also 14% of organic materials by 2014 and 60% by 2020. Such recyling goal can be considered into the organization’s buildings and practices. In addition, the city has organized the events related to zero waste and/or eco-responsibility (Ville de Montréal, 2016). The results of these efforts has been reflected by the results shown in Figure 4-15 with the GHG emissions produced over the period 2015 to 2018 in Montréal. It can been seen the highest production of GHG emissions over the period is attributed to 2015 with 1342.39 kt CO_2-eq, while 2018 accounting for 1219.29 kt CO_2-eq, had the least GHG emissions over the 3- year period. GHG emissions produced in 2016 and 2017 are 1262.38 kt CO_2-eq and 1231.81 kt CO_2-eq respectively. The trend shows a slight reduction which means the great success of reducing GHG emissions in this part for in Montréal.

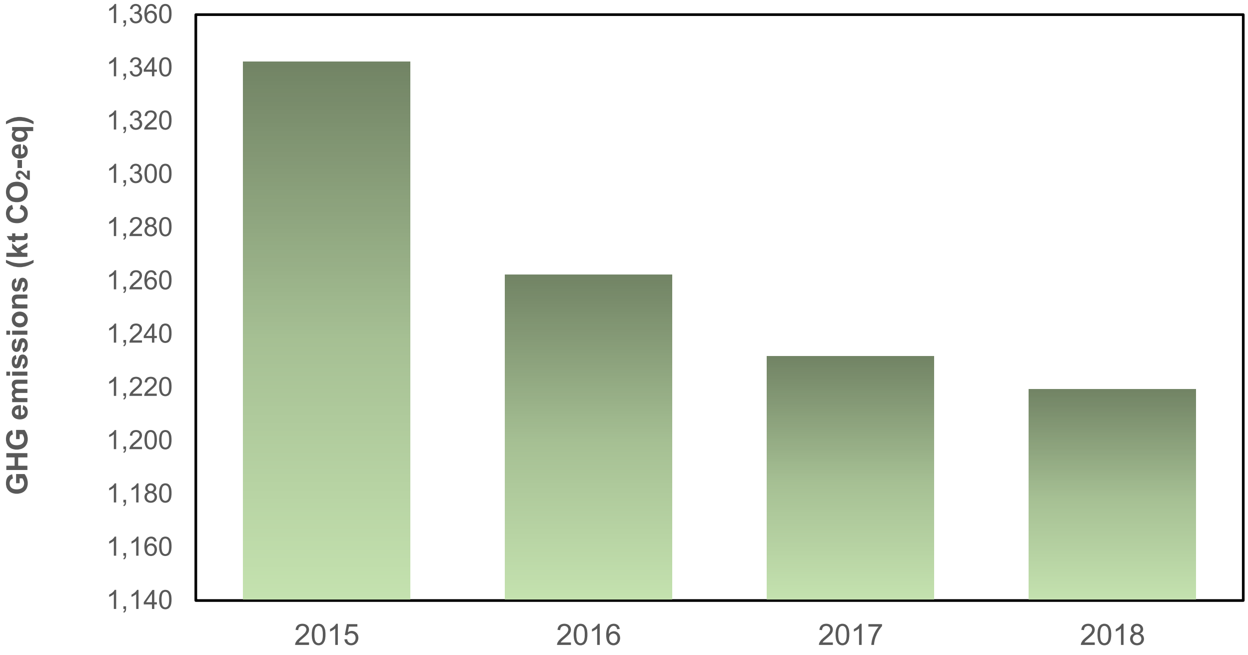

Figure 4-15 GHG emissions from Montreal municipal solid waste disposal in different years.

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4.8. Emissions from Wastewater Treatment

The Montréal region alone produces two-thirds of the wastewater in Québec. The treated wastewater in Montréal, obtained from Ville de Montréal, is 829,396, 800.0 m^3. Following the methodology, the amount of treated wastewater is multiplied by the concentration of BOD and nitrogen, which are 35 (g/m^3) and 60 (g/m^3), respectively (Henze and Comeau, 2008). Table 4-15 and Table 4-16 show the emission factors for CO_2, CH_4 and N_2O, which are 0.15 kg CH_4 per kg BOD and 0.0005 kg N_2O-N per kg N, respectively. The GWP values are shown in Table 4-17.

Table 4-15 Emission factor for CO_2 in wastewater treatment

Emission factor (kg CO_2/unit)	**Unit**	**Area**	**Reference**
0.5	M^3		(Gupta and Singh, 2012)
0.03	kg	India	
0.26	kg CO_2-eq /day/EP		(Gupta and Singh, 2012)

Table 4-16 Emission factor for N_2O and CH_4 in wastewater treatment

EF(g/Unit)	Gas type	Unit	Area	Reference
0.15	CH_4	kg BOD	Denmark	(National Environmental Research Institute, 2005)
0.03	CH_4	kg BOD	Noida	(Gupta and Singh, 2012)
0.26	CH_4	kg BOD		(National Environmental Research Institute, 2005)
0.15	CH_4	kg BOD		(National Environmental Research Institute, 2005)
0.65	CH_4	kg BOD		(Gupta and Singh, 2012)
0.80	CH_4	kg CO_2-eq /day/EP		(Listowski et al., 2011)
0.007	N_2O	person per year	Germany	(National Environmental Research Institute, 2005)
0.0032	N_2O	person per year	Netherland	(National Environmental Research Institute, 2005)
1.57	N_2O	kg N		(Gupta and Singh, 2012)
0.30	N_2O	kg CO_2-eq /day/EP	Noida	(Listowski et al., 2011)

Table 4-17 Global warming potential (GHG emissions protocol, 2016)

Species	Chemical Formula	Global Warming Potential
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

The treated wastewater for cities, Toronto, Calgary, Hamilton, Windsor and Regina has been extracted from MBN Canada report (Municipal Benchmarking Network Canada, 2016) shown in Figure 4-16 and calculated based on the developed methodology to obtain GHG emissions. The amount of wastewater produced in Montréal is the highest among the cities being compared, Calgary, Toronto, Windsor, Hamilton and Regina. According to the comparison of treated wastewater (Figure 4-16) Montréalers are the highest producers of wastewater and this city is one of the major treaters of wastewater. Then, it is followed by Toronto with small difference and Calgary and Windsor stand as the third and fourth highest treated wastewater. Hamilton and Regina with bigger difference and different scale too have the the least and second-least treated wastewater in both comparison of total treated wastewater and wastewater per capita. Wastewater produced 1,100.22 kt CO_2-eq in Montréal in 2016 which is compared with GHG emissions from wastewater treatment in Calgary, Toronto, Windsor, Hamilton and New York in Figure 4-17. Comparing GHG emissions from wastewater from Montréal with the cities, is found Montréal to be the largest driver of GHGs by wastewater. However, GHG emissions from wastewater treated from Toronto in 2016 accounts for 458.19 kt CO_2-eq, standing as the second-largest driver of GHG emissions by wastewater despite its population that was almost two times greater than the population of Montréal. Moreover, Montréal's treated wastewater amount is up to two times greater than the amount of wastewater treated in Toronto. Although treated wastewater per capita is approximately the same in Toronto, Calgary, and Windsor, Toronto is found to have emitted the highest total GHG emissions among these three cities. Even though New York City is more populous and bigger city in comparison to Windsor and Calgary, the GHG emissions produced by wastewater in New York City is lower than these two cities. Regina accounts for the lowest emissions in this sector. Residents in Hamilton and Regina producing 153.30 kg CO_2-eq and 32.1 kg CO_2-eq as the total GHG emissions from wastewater in 2016, produced GHG emissions less than 1 kg CO_2-eq per capita.

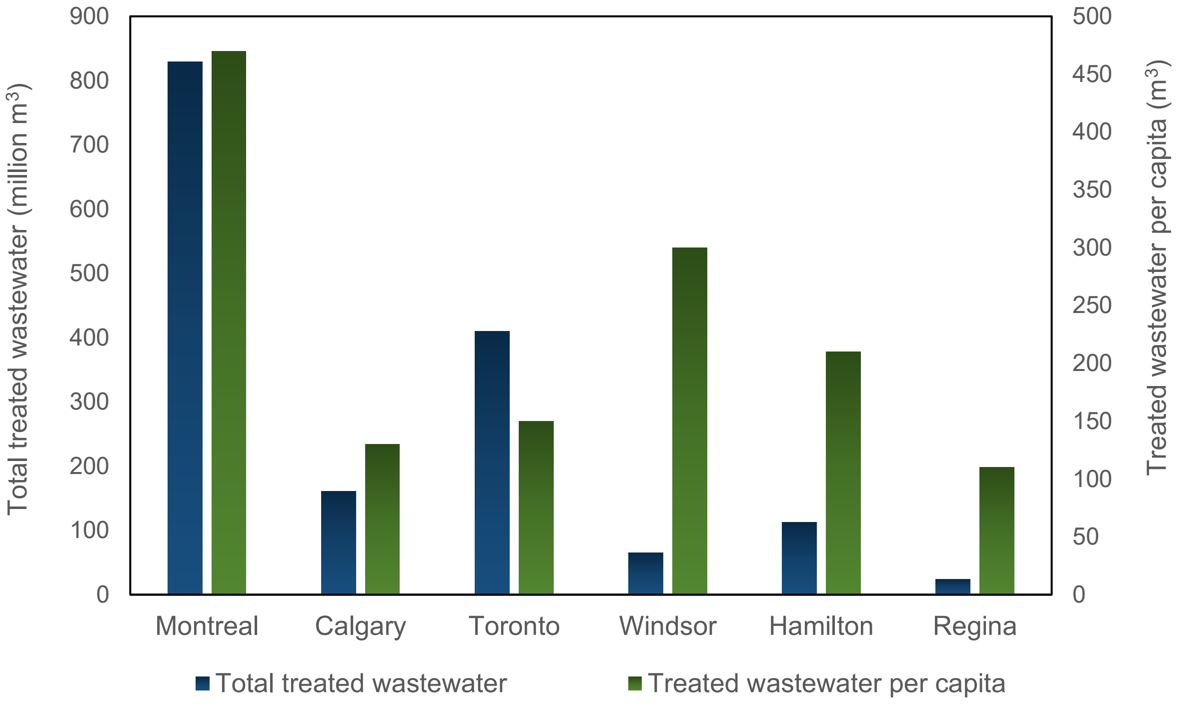

Figure 4-16 Treated wastewater in 2016.

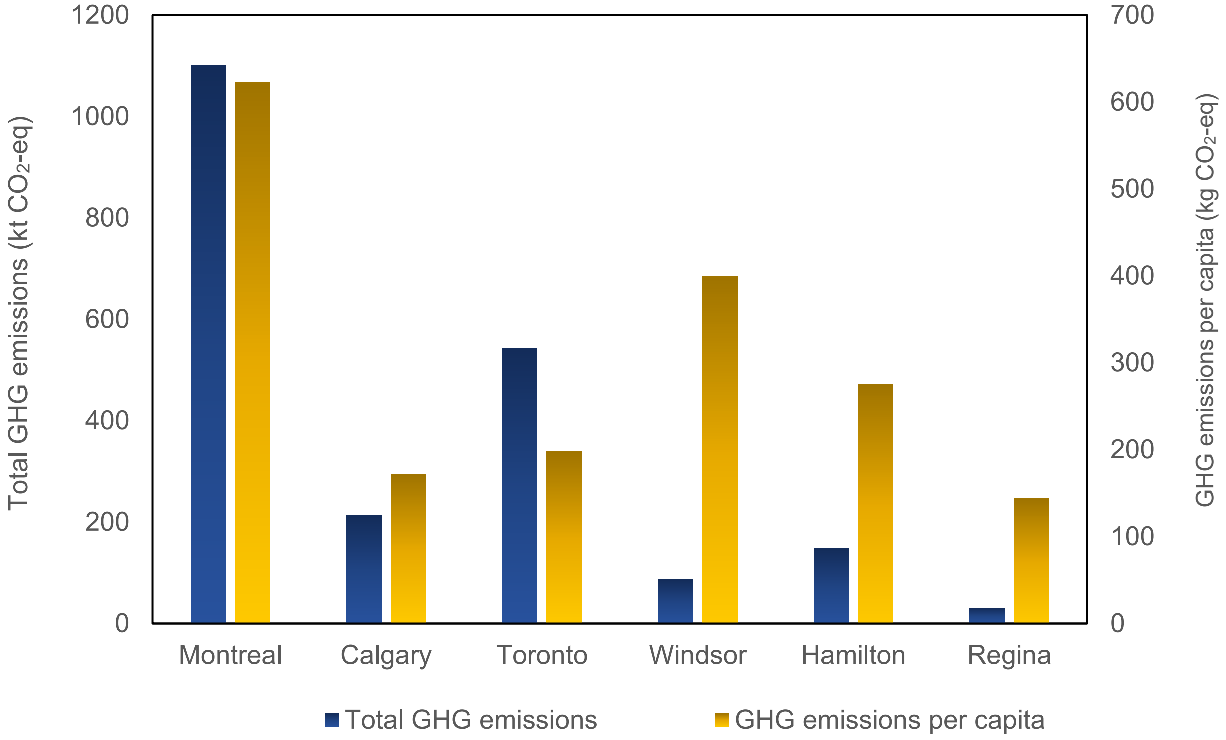

Figure 4-17 GHG emissions by wastewater in 2016.

The GHG emissions from wastewater treatment can be impacted by the total amount of wastewater. Therefore, reducing consumed water amount and harvesting rainwater can help reduce GHG emissions. Montréal has employed the installation of WaterSens certified plumbing and irrigation equipment, and low-water landscaping (xeriscaping) to reduce wastewater generation. The city has also established the necessary green infrastructure by directing water from gutters and spouts to permeable surfaces (Ville de Montréal, 2016).

4.9. Carbon Sequestration from Greenspace

To account for the carbon offset due to the absorption of CO_2 by trees in urban parkland, the number of trees is multiplied by the absorption factor per tree. There is no data for the total number of trees in Montréal island, but the report of MBN Canada (Municipal Benchmarking Network Canada, 2016) has published information in terms of two categories: maintained parkland and natural parkland. Hectares of maintained and natural parkland per 100,000 people have been noted to be 124 and 106, respectively Montréal, as of 2016. Based on the average amount of space occupied by a single tree multiplied by the total area of parkland in Montréal, the number of trees is assumed to be 481,667. The absorption factor, it should be noted, is defined as the average amount of CO_2-eq which can be absorbed by a single tree per year, which is 22 kg CO_2-eq The carbon offset from trees in Montréal in 2016 is thus calculated to be 10,596 t CO_2-eq. To find the net GHG emission produced in Montréal in 2016, the carbon offset amount due to the absorption of CO_2 by trees in urban parkland is subtracted from the total emissions to obtain the net GHG emissions emitted to the atmosphere from Montréal in 2016.

The city has made the plan to protect and enrich the urban forest and biodiversity by planting 300,000 trees on public and private property within Montréal by 2025. It will increase the total number of trees to around 800, 000 trees by 2025 and 17 t CO_2-eq will be absorbed by the trees by 2025 which is about 2 times as the amount of CO_2-eq absorbed in 2016. Furthermore, the city also aimed to add 1,000 hectares to land areas already protected in the urban area. For the buildings, also thers is a plan trying to double the number of green roofs on municipal buildings (Ville de Montréal, 2016).

4.10. Total GHG Emissions from Montreal

A total of 13.310 Mt CO_2-eq is found to have been emitted in Montréal in 2016 with consideration of CO_2 absorbption by green space and without these emission absorption the total GHG emissions in Montréal in 2016 would be 13.32 Mt CO_2-eq. The results obtained are applied to different sectors considered in the case study (see Figure 4-18 and Figure 4-19) private vehicles accounted for 52% of total GHG emissions in Montréal in 2016, standing as the largest driver of GHG emissions. The action plan has been taken to reduce GHG emissions from private vehicles through the improvement of public transportation. Natural gas constituted by 26% as the second-largest driver of GHG emission. Some actions have been taken by the city to reduce the use of natural gas and replace it with renewable energy for heating. The city is trying to provide financial incentives for buildings that are moving to renewable energy, instead of natural gas. Unlike oil heating, the city does not have specific target for forbidging natural gas by 2020 but they will provide more actions for this source of energy in the future. Solid waste disposal with 1, 262.38 kt CO_2-eq, representing the third-largest GHG emissions in Montréal in 2016. Wastewater treatment, due to the large amount of treated wastewater, is found to have been the fourth-highest level of GHG emissions, accounting for 8% of total GHGs. Although only 1% of electricity is generated by thermal power, 2% of the total GHG emissions in Montréal in 2016 is attributed to electricity. Whereas, oil used by a few households in the city for heating, accounted for 2% of the total GHG emissions with 227.65 kt CO_2-eq. Therefore, the city has developed plans to eliminate oil used for heating by 2020. Urban transportation network with primary fuel of diesel constituted only 1% of total GHG emissions in Montréal in 2016.

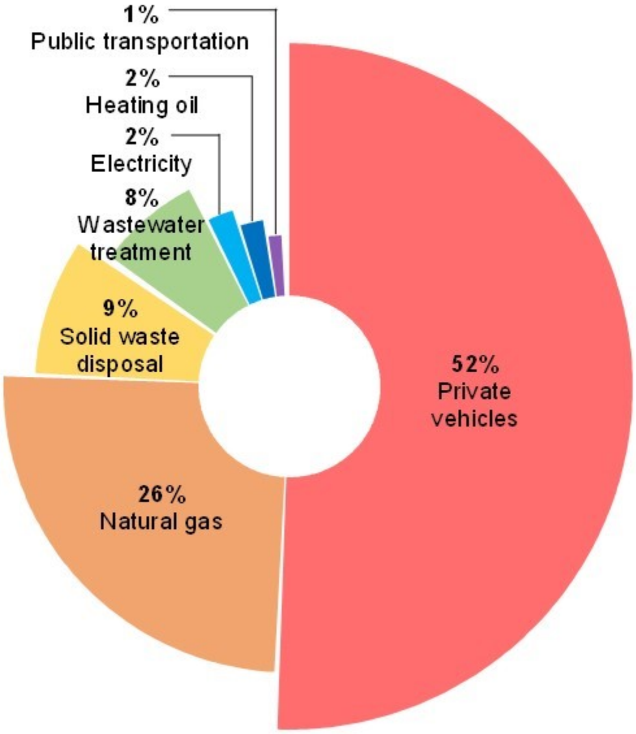

Figure 4-18 The ratios of total GHG emissions from Montréal in 2016.

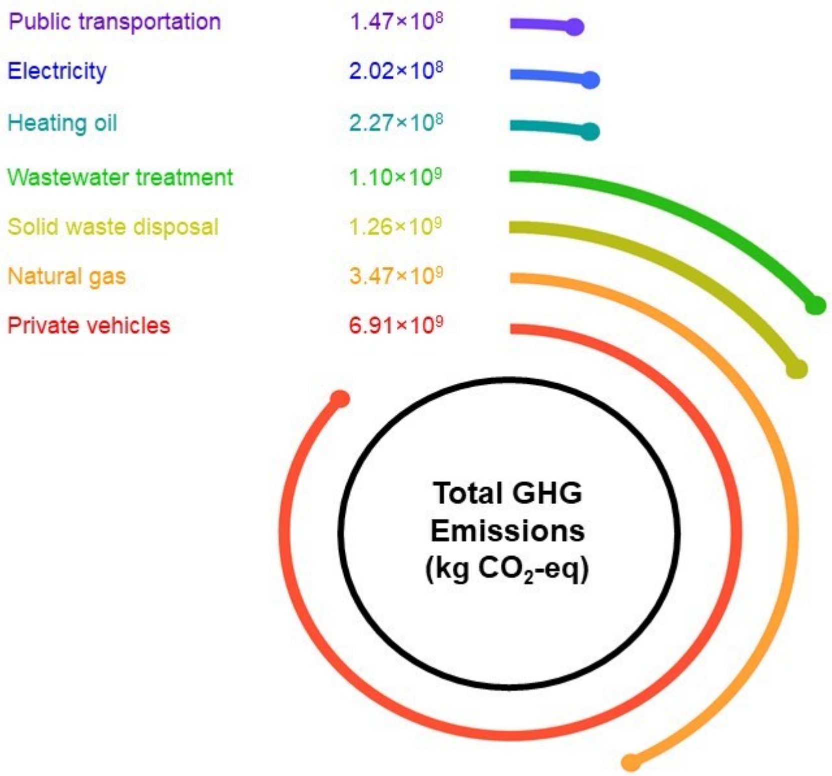

Figure 4-19 Total GHG emissions from Montréal in 2016.

A per capita comparison of the sectors (Figure 4-20) shows the high rate of GHG emissions by private vehicles in 2016, Montréalers emitted over 7,000 kg CO_2-eq per capita in 2016 by driving private vehicles. Natural gas as the second-highest GHG emissions in Montréal in 2016 emitted over 5, 000 kg CO_2-eq. Solid waste produced by each resident in Montréal in 2016 emitted around 800 kg CO_2-eq to the atmosphere. The amount of emissions from treated wastewater in Montréal, at 1.1 Mt CO_2-eq, represented roughly 1,000 kg CO_2-eq per capita. Using oil as a sourse for providing heating by households produced around 100 kg CO_2-eq per capita. The only relatively low level of GHG emissions production per capita is attributed to the Suburban Transportation Network (STN), with less than 1 kg CO_2-eq in 2016.

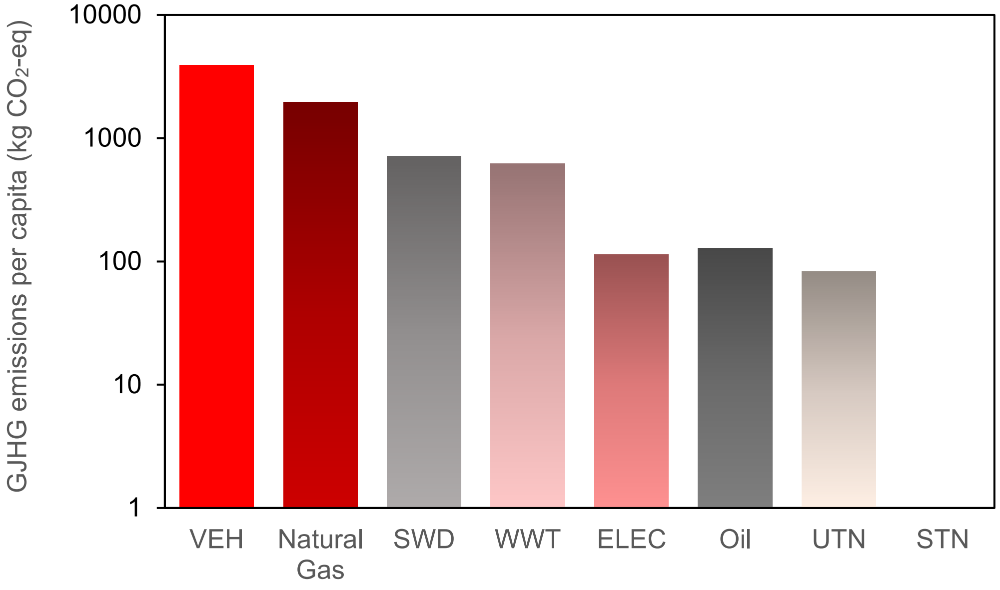

Figure 4-20 Total GHG emissions per capita in Montréal by sector in 2016.

A GHG emissions inventory of New York City (The City of New York, 2017) is one of the reports compared with the results for Montréal. This report categorizes the factors contributing to municipal GHG emissions as follows:

- Energy used by buildings and other stationary sources, and fugitive emissions from natural gas distribution within the city limits of NYC
- On-road transportation, railways, marine navigation, and aviation within city limits
- Wastewater treatment within the city boundary and solid waste generated within the city but disposed outside of the city

The total GHG emissions produced in New York City in 2016 was 52 Mt CO_2-eq with around 8.615 million population, and each resident in New York City was responsible for 6.1 MT CO_2-eq in 2016. This report shows that the stationary energy sector, including the combustion of natural gas (31%), the use of electricity (25%), and the combustion of gasoline (24%), produced the highest GHG emissions in New York City in 2016 among the categories considered. The second-highest emitter was transportation, while the third was waste and wastewater. In comparing of Montréal and New York City, it is noted that the highest-emitting sector in Montréal is private transportation. While the data on emissions from the transportation sector in New York City is not further categorized into private and public, even with private and public transportation combined it is only the second-largest driver of GHG emissions. Waste and heating, meanwhile, are found to be at the same level in both cities. In comparing Montréal to Toronto for the same year, the transportation sector accounts for over 40% of Toronto's overall GHG emissions, approximately the same as the proportion in Montréal.

The results obtained are also compared with other cities such as Helsinki in Finland, Batangas in the Philippines, Okayama in Japan, Dallas in the United States, and others, as shown in Figure 4-21, which illustrates that among all these cities the highest GHG emission was produced by New York City in 2016 while the second-highest producer was, United kingdom. Cape Town, South Africa, Buenos Aires, Argentina, Dallas, in the United States, and Toronto ranked third, fourth, fifth, and sixth as GHG emitters, with Montréal following Toronto in the seventh position in this comparison.

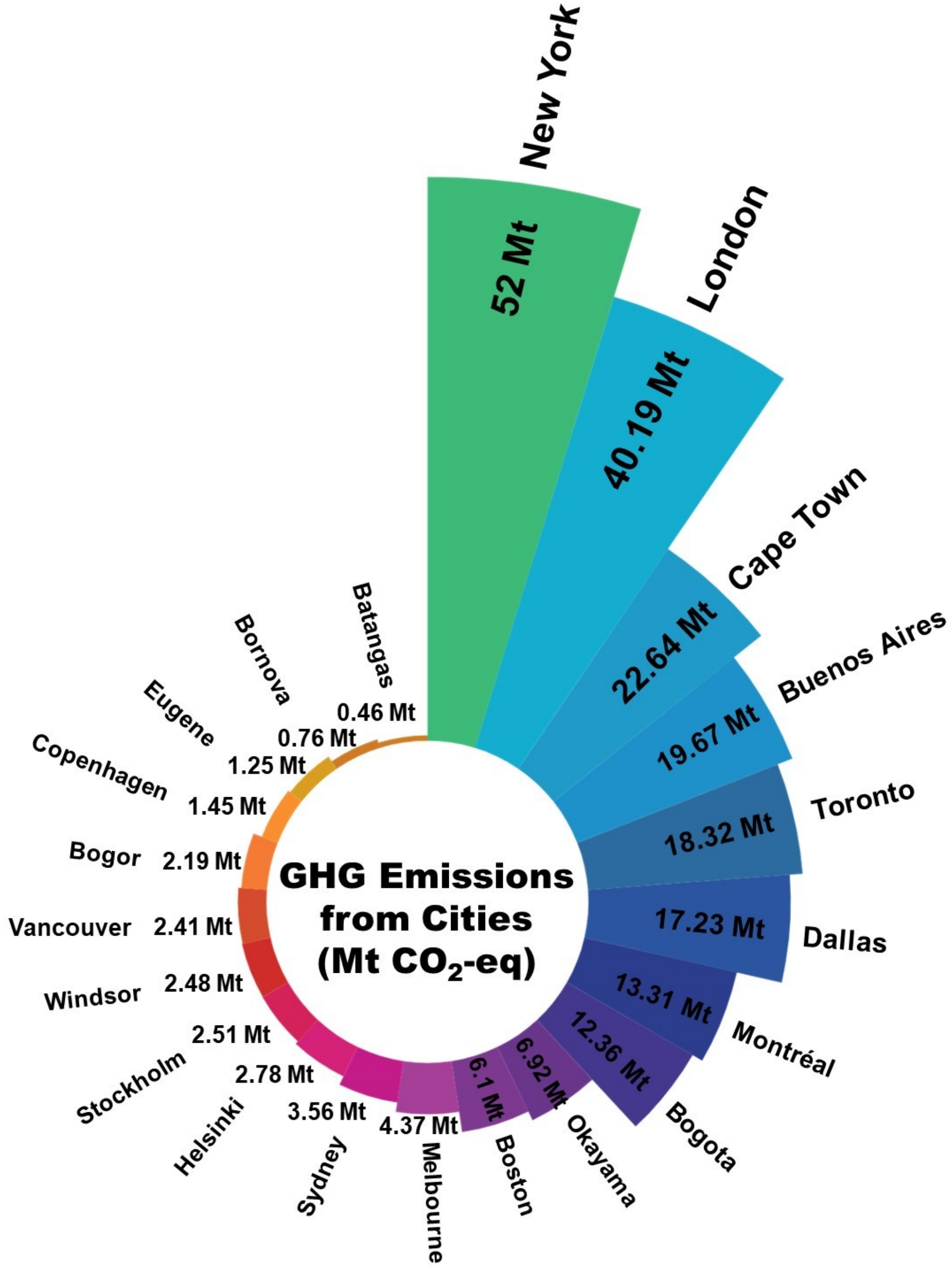

Figure 4-21 GHG emissions from other cities in 2016.

Montréal is committed to reduce GHG emissions by 30% compared to 1990 levels by 2020 and by 80% by 2050 (Ville de Montréal, 2016). That is why the city has provided different plans which are open to the public. There are four sustainable development priorities in Montréal including (i) reducing GHG emissions and dependence on fossil fuels, (ii) adding vegetation, increasing biodiversity and ensuring the continuity of resources, (iii) ensuring access to sustainable, human-scale and healthy neighbourhoods, and (iv) making the transition toward a green, circular and responsible economy. The correspding action plans have been developed under these priorities to meet the targets. All these action plans show how people's life style or their behavoiur can affect global GHG emissions.

CHAPTER 5. SENSITIVITY ANALYSIS

5.1. Sensitivity of Emission Factors

A sensitivity analysis is conducted to determine which factor has the most significant effect on GHG emission production. The methodology developed in the present study includes many factors, such as emission factors, fuel economies, travel distances, average weight of trains and concentration of BOD and nitrogen. To clarify the results, the factors in this study are divided into two categories: emission factors and other factors. The sensitivity analysis is carried out using Minitab software, and the results are shown in the figures below. In this section, emission factors are evaluated.

There are 10 emission factors evaluated, the emission factor of heating fuel, the emission factor of energy (gasoline), the emission factor of energy (diesel), the emission factor of energy (biodiesel), the emission factor of suburban public transportation type, the emission factor of fuel consumption (light vehicles), emission factor of fuel consumption (medium and heavy vehicles), the emission factor for CH_4 in wastewater, the emission factor for N_2O in wastewater, and the emission factor for electricity generated by oil-fired power plants, as shown in Table 5-1. Table 5-2 demonstrates the alias relationships for 2^{10-4} fractional factorial analysis and solutions of 2^{10-4} fractional factorial analysis, respectively.

Table 5-1 Alias relationships for 2^{10-4} fractional factorial analysis about emission factors

Factor	Definition	Low Level (-1)	High Level (+1)
[A]	Emission factor of heating fuel	1.888	1.926
[B]	Emission factor of the energy (Gasoline)	55.44	83.16
[C]	Emission factor of the energy (Diesel)	59.26	88.88
[D]	Emission factor of the energy (Biodiesel)	57.14	85.7
[E]	Emission factor of suburban public transportation type	0.01216	0.01824
[F]	Emission factor of fuel consumption (Light vehicles)	1.76	2.64

[G]	Emission factor of fuel consumption (medium and Heavy vehicles)	2.064	3.096
[H]	Emission factor for CH_4 in wastewater	0.03	0.26
[J]	Emission factor for N_2O in wastewater	0.0004	0.0006
[K]	Emission factor for electricity generated by oil-fired power plant	676000	1014000

Table 5-2 Matrix for 2^{10-4} fractional factorial design regarding emsission factors

EF_HEAT	**EF_ENERGY (Gasoline)**	**EF_ENERGY (Diesel)**	**EF_ENERGY (Biodiesel)**	**EF_SPTN**	**EF_FUEL (Light vehicle)**	**EF_FUEL (Medium & Heavy vehicle)**	**EF_ CH_4**	**EF_ N_2O**	**EF_EGS (Thermal power)**
1	-1	-1	-1	-1	1	-1	1	-1	-1
1	-1	1	1	-1	1	-1	1	1	1
-1	-1	1	-1	-1	1	1	1	1	-1
1	1	1	1	1	1	1	1	1	1
1	1	-1	1	1	1	-1	-1	1	-1
-1	-1	-1	1	-1	-1	-1	-1	-1	1
-1	-1	1	1	1	1	-1	-1	1	1
1	1	-1	-1	-1	1	1	1	1	1
1	1	1	-1	-1	1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	1	1	1	1
-1	1	-1	-1	1	-1	-1	1	1	1
1	1	-1	-1	-1	-1	-1	-1	1	1
-1	-1	-1	1	1	1	1	1	1	-1
1	1	-1	-1	1	-1	-1	-1	-1	-1
-1	-1	1	-1	-1	-1	-1	-1	1	-1
1	-1	1	-1	-1	1	1	-1	-1	1
1	-1	1	-1	1	-1	-1	1	1	-1
-1	1	1	1	1	-1	-1	1	-1	-1
1	1	-1	1	-1	-1	1	1	-1	1
-1	1	1	1	-1	1	1	-1	1	1

1	-1	-1	-1	1	-1	1	-1	1	1
-1	1	-1	-1	-1	-1	-1	1	-1	-1
1	1	1	1	-1	-1	-1	-1	-1	-1
1	-1	-1	-1	1	1	-1	1	1	1
1	1	1	1	1	-1	-1	-1	1	1
1	-1	-1	1	-1	-1	-1	1	1	-1
1	-1	-1	1	1	1	1	-1	-1	1
-1	1	1	-1	1	1	-1	1	1	-1
-1	1	-1	1	-1	1	-1	1	1	-1
-1	-1	1	-1	1	1	1	1	-1	1
1	1	-1	-1	1	1	1	1	-1	-1
1	-1	1	-1	1	1	1	-1	1	-1
-1	1	1	-1	1	-1	1	-1	1	-1
-1	-1	-1	-1	1	-1	1	1	-1	-1
-1	-1	1	1	-1	1	-1	-1	-1	-1
1	1	-1	1	1	-1	1	1	1	-1
-1	1	-1	1	1	1	-1	1	-1	1
-1	1	1	-1	-1	1	-1	1	-1	1
-1	-1	1	-1	1	-1	-1	-1	-1	1
-1	-1	-1	1	-1	1	1	1	-1	1
1	1	1	-1	1	1	-1	-1	-1	1
1	-1	-1	-1	-1	-1	1	-1	-1	-1
-1	1	-1	1	1	-1	1	-1	-1	1
1	1	1	-1	1	-1	1	1	-1	1

1	-1	1	1	-1	-1	1	-1	1	1
-1	-1	-1	-1	1	1	-1	-1	-1	-1
1	-1	-1	1	-1	1	1	-1	1	-1
-1	1	-1	-1	-1	1	1	-1	-1	-1
1	1	1	1	-1	1	1	1	-1	-1
-1	-1	-1	1	1	-1	-1	-1	1	-1
1	1	1	-1	-1	-1	1	1	1	-1
-1	-1	1	1	1	-1	1	1	1	1
1	-1	1	-1	-1	-1	-1	1	-1	1
-1	1	1	1	1	1	1	-1	-1	-1
1	1	-1	1	-1	1	-1	-1	-1	1
-1	-1	1	1	-1	-1	1	1	-1	-1
1	-1	1	1	1	-1	1	-1	-1	-1
1	-1	-1	1	1	-1	-1	1	-1	1
-1	1	-1	1	-1	-1	1	-1	1	-1
-1	1	-1	-1	1	1	1	-1	1	1
-1	-1	-1	-1	-1	1	-1	-1	1	1
-1	1	1	1	-1	-1	-1	1	1	1
1	-1	1	1	1	1	-1	1	-1	-1
-1	1	1	-1	-1	-1	1	-1	-1	1

The pareto chart of the factors are shown in Figure 5-1(A). Since private vehicles are found to have produced the highest rate of GHG emissions in Montréal in 2016 at 6.91 Mt CO_2-eq, “G”, standing for emission factor of fuel consumption (medium and heavy vehicles), plays the primary role in this assessment. The GHG emitted to the atmosphere only by heavy vehicles in Montréal in 2016 was 4.02 Mt CO_2-eq. “H”, meanwhile, which represents the emission factor for CH_4 in wastewater treatment, is the second-most significant factor and is associated with 1.1 Mt CO_2-eq of emissions, accounting for 8% of the total. The third-most significant factor, represented as “F”, is the emission factor for light vehicles, where this sector produced 2.88 Mt CO_2-eq in emissions. The emission factor for electricity generated by oil-fired power plants (represented as “K”) is the fourth-most important factor, although electricity is found to have been one of the least significant drivers of GHG emissions in Montréal in 2016. The next factor, “A”, is the emission factor for heating, where natural gas is the next-most significant factor after private vehicles. Figure 5-1(B) illustrates the main effects of four most major emission factors. When the emission factor for heavy vehicles (G) is at the low level of 2.064 kg CO_2-eq/km, the total GHG emission in Montréal is around 12, 200 kt CO_2-eq, while the emission reached to 14,000 kt CO_2-eq indicating at high level of this emission factor.

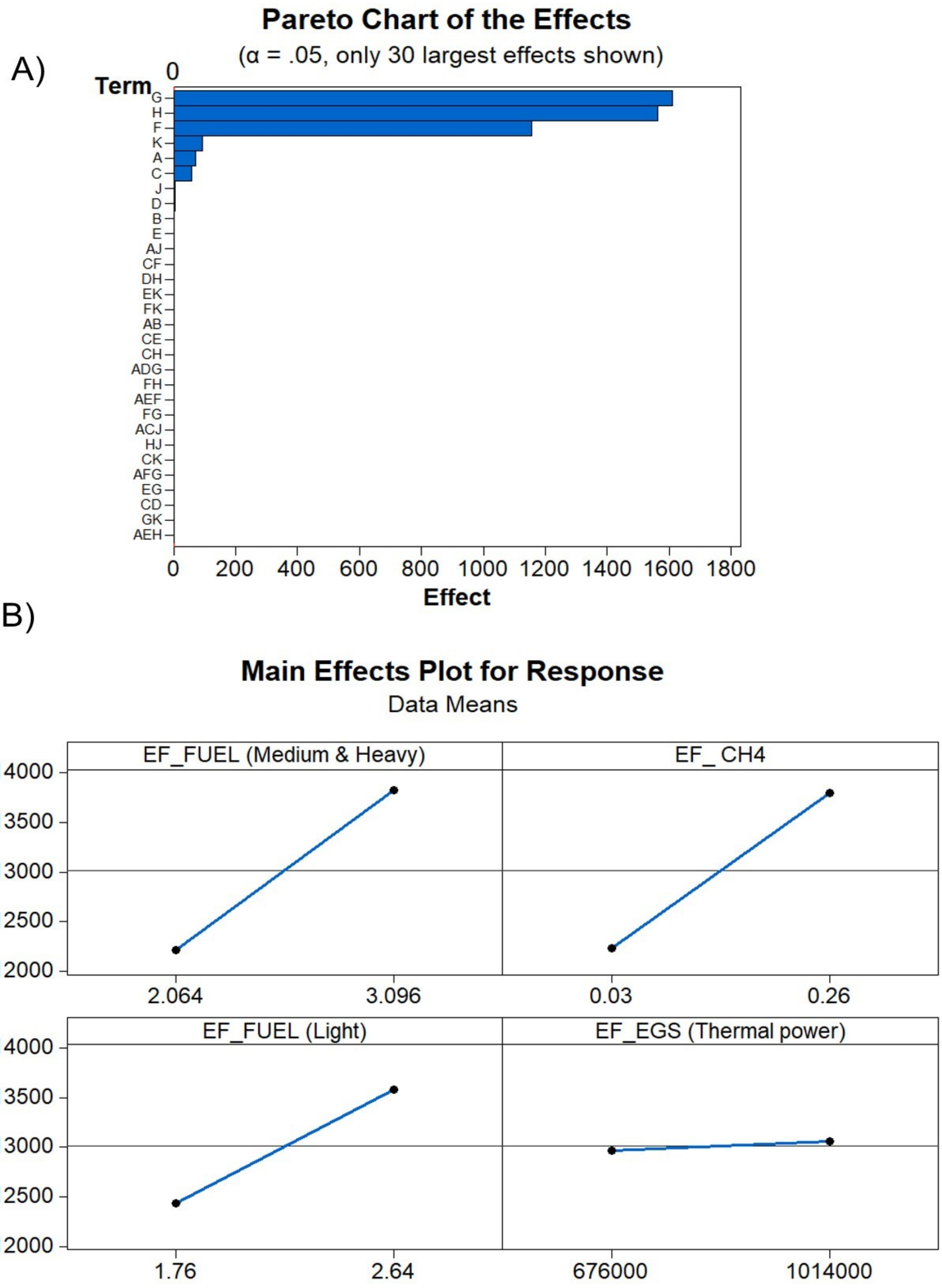

Figure 5-1 Factorial analysis results: (A) Pareto chart of the effects (B) Main effect plots for different factors

5.2. Sensitivity of Other Factors

In this section, the significance of the following factors is evaluated: TTD (total travel distance of suburban public), AW (average weight of suburban public), ATD_VEH (average travel distance by light and heavy vehicles), DOC_SW (Degradable organic carbon in solid waste), F_DOC (fraction of DOC dissimilated), CBOD (concentration of BOD in raw wastewater), CN (concentration of Nitrogen in raw wastewater) and Ratio_ELEC (electricity generation ratio), and oil consumption for heating. In total there are 10 factors, and the chosen design is 10-4. Table 5-3 shows the terms and factors evaluated in this section, while Table 5-4 illustrates the relations for fractional factorial analysis.

Table 5-3 Alias relationships for 2^{10-4} fractional factorial analysis about other factors

Factor	**Definition**	**Low Level (-1)**	**High Level (+1)**
[A]	Total travel distance of suburban public transportation vessel	42157.5	183806.7
[B]	Average weight of suburban public transportation vessel	94.332	141.496
[C]	Average travel distance for light vehicles	11840	17760
[D]	Average travel distance for heavy vehicles	72000	108000
[E]	Degradable organic carbon in solid waste	0.12	0.18
[F]	Fraction of degradable organic carbon dissimilated	0.616	0.924
[G]	Concentration of BOD_5 in wastewater	0.00028	0.00042
[H]	Concentration of Nitrogen in raw wastewater	0.000048	0.000072
[J]	Ratio of electricity generation from different sources	0.01	0.99
[K]	Oil consumption	18	108

Table 5-4 Matrix for 2^{10-4} fractional factorial design regarding the other factors

TTD	**AW**	**ATD_VEH (Light)**	**ATD_VEH (Heavy)**	**DOC_SW**	**F_DOC**	**CBOD**	**CN**	**RATIO_ELEC**	**Oil consumption**
1	-1	1	-1	1	-1	-1	1	1	-1
1	-1	1	1	-1	1	-1	1	1	1
-1	1	-1	1	1	-1	1	-1	-1	1
-1	-1	-1	-1	1	1	-1	-1	-1	-1
1	1	-1	-1	1	1	1	1	-1	-1
1	-1	1	-1	-1	1	1	-1	-1	1
-1	-1	1	-1	1	-1	-1	-1	-1	1
1	1	1	1	-1	1	1	1	-1	-1
1	-1	1	-1	-1	-1	-1	1	-1	1
-1	1	-1	1	1	1	-1	1	-1	1
-1	-1	-1	-1	1	-1	1	1	-1	-1
-1	1	1	-1	-1	-1	1	-1	-1	1
-1	1	-1	1	-1	-1	1	-1	1	-1
-1	1	-1	-1	1	1	1	-1	1	1
-1	-1	-1	1	-1	1	1	1	-1	1
1	-1	-1	1	1	-1	-1	1	-1	1
1	1	1	-1	-1	1	-1	-1	1	-1
1	1	1	-1	1	-1	1	1	-1	1
-1	1	-1	-1	-1	-1	-1	1	-1	-1
1	-1	-1	1	-1	-1	-1	1	1	-1

-1	-1	-1	1	-1	-1	-1	-1	-1	1
1	1	-1	1	-1	1	-1	-1	-1	1
1	1	-1	-1	-1	-1	-1	-1	1	1
1	1	-1	1	-1	-1	1	1	-1	1
-1	-1	1	1	-1	-1	1	1	-1	-1
1	1	1	-1	-1	-1	1	1	1	-1
-1	-1	1	-1	-1	1	1	1	1	-1
-1	1	-1	-1	1	-1	-1	1	1	1
-1	-1	1	-1	-1	-1	-1	-1	1	-1
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1	1	-1	1	1	1	-1	-1	1	-1
-1	1	-1	-1	-1	1	1	-1	-1	-1
-1	-1	1	1	1	-1	1	1	1	1
-1	-1	1	-1	1	1	1	1	-1	1
-1	-1	-1	-1	-1	1	-1	-1	1	1
-1	1	1	-1	1	1	-1	1	1	-1
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1	-1	1	1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	-1	-1	1	1	1	1
1	1	-1	-1	1	-1	-1	-1	-1	-1
1	-1	-1	-1	-1	1	-1	1	-1	-1
-1	1	1	1	-1	-1	-1	1	1	1
-1	1	1	-1	1	-1	1	-1	1	-1
1	-1	1	1	-1	-1	1	-1	1	1
1	-1	1	-1	1	1	1	-1	1	-1
1	-1	1	1	1	1	-1	1	-1	-1
-1	1	1	1	-1	1	1	-1	1	1
-1	1	1	1	1	1	1	-1	-1	-1
1	1	1	1	1	-1	-1	-1	1	1
-1	1	1	1	1	-1	-1	1	-1	-1
1	-1	-1	-1	1	-1	1	-1	1	1
1	-1	-1	-1	-1	-1	1	-1	-1	-1
-1	1	1	-1	-1	1	-1	1	-1	1
1	-1	-1	1	-1	1	1	-1	1	-1
-1	-1	1	1	1	1	-1	-1	1	1

Figure 5-2(A) shows that term “D”, which represents average travel distance for heavy vehicles, has the most important impact among the factors, while average travel distance for light vehicles stands as the second-most important factor “C”, and was the largest driver of GHG emissions with natural GHG in Montréal in 2016. “E”, representing degradable organic carbon, and “F”, standing for fraction of degradable organic carbon dissimilated, are the third- and fourth-most significant factors, respectively, since municipal solid waste disposal constituted only 9% of the total GHG emission produced in Montréal in 2016 with 605.94 kt CO_2-eq. Oil consumption (“K”) is found to have played a minimal role as the fifth factor, while the concentration of BOD5 is the sixth-most significant factor, whereas wastewater is found to have produced the second-highest GHG emissions in Montréal in 2016. In other cities, stationary energy, including electricity and heating, is the primary driver of GHGs, such that the electricity generation ratio is likely to play the primary role in determining the amount of emissions derived from electricity generation. However, in the case of Montréal, where 99% of electricity is from hydropower and only 1% is from oil-fired power plants, electricity generation is just the seventh-largest driver of GHG emissions. Figure 5-2 (B) shows the main effects plot illustrating the variation of each factor how impact has on the total GHG emissions. Figure 5-2(B) shows when the average travel distance of heavy vehicles is at the low level, there will be the GHG emission of around 13,000 million kg CO_2-eq, while the emission can reach around 14, 500 million kg CO_2-eq at the high level of this factor. With low level of average travel distance by light vehicles, total GHG emission will be around 13,400 kt CO_2-eq and total GHG emissions will be 14,300 kt CO_2-eq with high level of that factor.

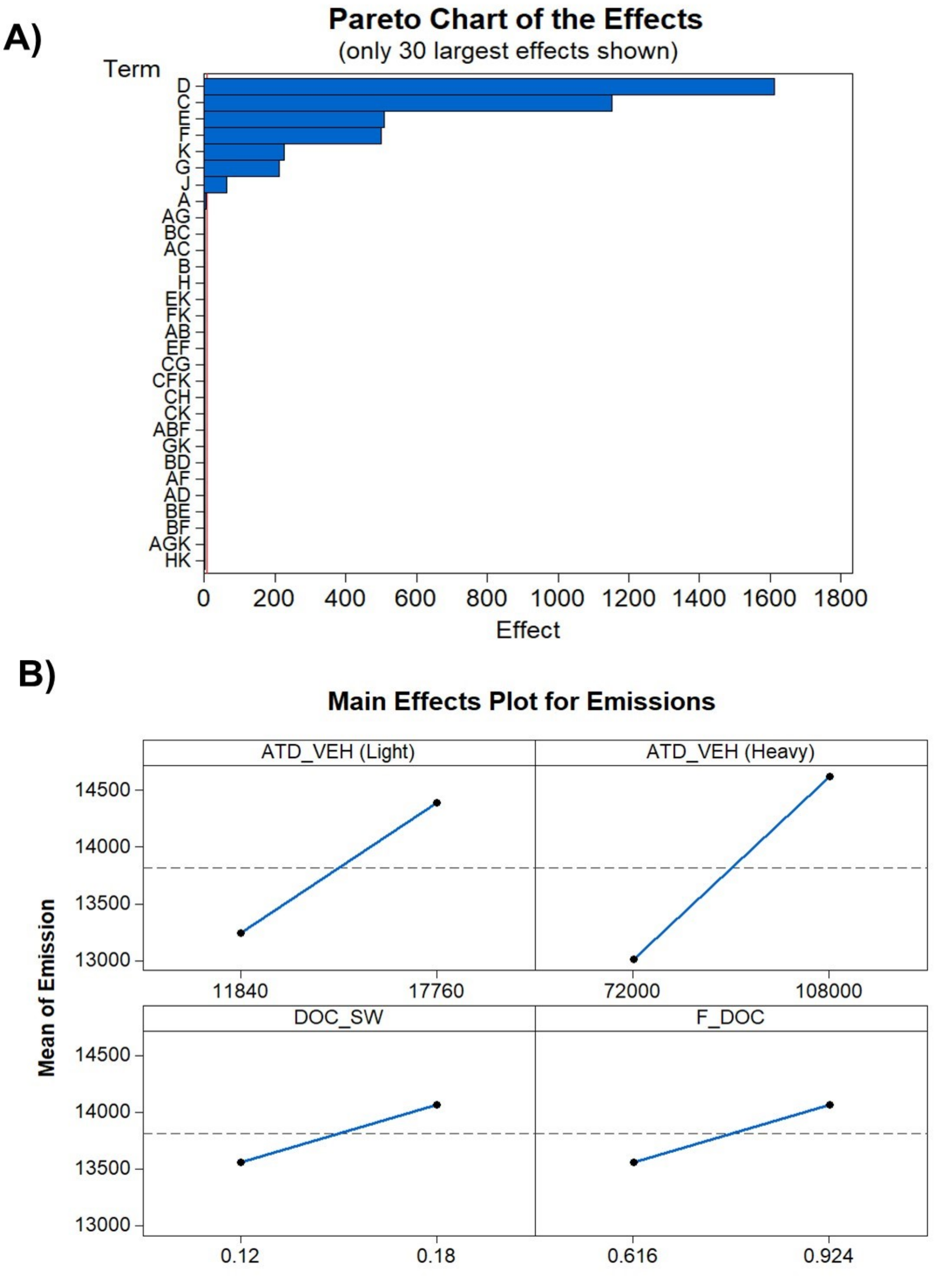

Figure 5-2 Factorial analysis results: (A) Pareto chart of the effects (B) Main effect plots for different factors

CHAPTER 6. CONCLUSIONS

6.1. Summary

Due to the lack of a detailed methodology for the assessment of urban GHG emissions from human activities such as heating and electricity demand, transportation, and waste processing and wastewater processing, this study has sought to identify the primary contributors to urban GHG emissions. A detailed methodology was then developed which encompasses all the contributing factors defined. The methodology is then applied to Montréal as a case study. The data collected for the purpose of developing treatment and implementing the methodology included natural gas consumption data, the volume of wastewater treated, the amount of municipal solid waste processed, electricity consumption data, and the total area of urban parkland. With regard to the emission factor, a robust database has been created for use in future studies. The data has been obtained from different organizations, annual reports, academic publications, and websites. The results obtained, it should be noted, have been presented to the Montréal city council, as well as to Energir, i.e., the company responsible for the distribution of natural gas in Montréal, in order to disseminate the knowledge obtained and the methodology developed, and to verify the provided activity data. The results have also been compared with data from other cities in terms of both individual sectors as well as total GHG emissions.

6.2. Research Achievements

In this study, many reports and papers have been reviewed to determine the key factors contributing to municipal GHG emission production. A comprehensive and detailed methodology for urban GHG emissions has been developed for urban GHG emissions inventory which considers all the municipal sectors contributing to GHG emission production. Moreover, a database has been created for urban GHG emission assessment. A wide range of emission factors has been considered with different units and different sources in each sector for different locations. This database will assist researchers in future studies to identify a suitable emission factor for each source based on the jurisdiction under study. Finally, an assessment of GHG emissions in Montréal has been conducted according to the developed method. As mentioned, the results also have been presented to Montréal’s city council.

6.3. Recommendations for Future Research

Further studies should be conducted to build on this analysis by considering GHG emissions from ports and airports. Furthermore, given that scope 3 is optional in each GHG emissions inventory, this study focused only on scopes 1 and 2. Future studies can, in addition to considering scopes 1 and 2, take into account the most significant aspects of scope 3, such as commuting employees, which requires the development of a comprehensive methodology for obtaining accurate commuter data. Furthermore, improving the model for calculating emissions from landfills is another aspect of scope 2 which requires further study.

Urban building emission related to energy efficiency is one option to reduce GHG emissions. To reduce GHG emissions in urban areas, though, the first step is to identify the key factors contributing to GHG emissions, while the final step is to evaluate the efficacy of mitigation measures introduced. For this reason, the development of an urban GHG emission assessment software can be helpful for governments.

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