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Energy Benchmarking And Energy Saving Assessment In High-Rise Multi-Unit Residential Buildings

Yirong Huang
Ryerson University

ENERGY BENCHMARKING AND ENERGY SAVING ASSESSMENT IN HIGH-RISE MULTI-UNIT RESIDENTIAL BUILDINGS

By

Yirong Huang

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Xiamen University, Xiamen, Fujian China, 2007

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AUTHOR'S DECLARATION

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Abstract

The purpose of energy benchmarking is to promote efficient use of energy. Knowing that the energy used by a building is excessive is the first step in making positive changes. Based on an energy benchmark, one can estimate the potential in energy and cost savings when pursuing better performance.

This thesis developed weather normalized energy benchmarking of 45 gas-heated high-rise multi-unit residential buildings (MURBs) in Toronto. The weather normalized annual energy consumption (NAC) was calculated by the PRInceton Scorekeeping Method (PRISM). The NACs are in the range from 242 to 453 kWh/m^2. The energy saving assessment showed that 24 MURBs had NACs changes, which ranged from 45.6 kWh/m^2 increase to 103.7 kWh/m^2 decrease.

The NACs, calculated by the simple ratio weather normalization (SRWN) method and ENERGY STAR® Portfolio Management (PM) method were comparable to PRISM results. However, the SRWN method tends to overestimate the energy saving by 23% while PM underestimates it by 21%.

Acknowledgement

This thesis would not have been possible without the kind support from the Dr. Alan S. Fung. I would like to give my special thanks to him for being a great mentor and a role model to me. His guidance on the expertise enables me to complete the thesis. Moreover, his great work ethic and passion is a valuable lesson to me.

I would also like to acknowledge all funding partners: City of Toronto, Canada Mortgage Housing Corporation (CMHC), Enbridge Gas Distribution (EGD), Ontario Municipal Affairs and Housing (MAH), and Mitacs. I would like to thank Ms. Aderonke Akende from City of Toronto for coordinating the data for the research.

I would like to thank to my fellow project partner Ms. Mahssa Ghajarkhosravi for her wonderful work on water and solid waste benchmarking. With her work, we were able to obtain a deeper insight of utility consumption in MURBs.

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Last but not least, I would like to give my appreciation to my parents and fiancé for unconditional support during my study. With their love and care, I was able to concentrate on the completion of the thesis.

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Nomenclature

CDD	Cooling Degree-days
GTA	Greater Toronto Area
HDD	Heating Degree-days
MURB	Multi-Unit Residential Building
NAC	Normalized Annual Consumption
NEUD	National Energy Use Database
PM	(ENERGY STAR®) Portfolio Manager
PRISM	PRInceton Scorekeeping Method
SHEU	Survey of Household Energy Use
SRWN	Simple Ratio Weather Normalization
TCHC	Toronto Community Housing Corporation

Chapter 1

1 Introduction

1.1 Background

Household energy conservation has been a topic of interest within social economic and environmental research for the past few decades (Abrahamse et al., 2005). Current energy consumption trends put the environment at risk. In 2008, the percentages of non-renewable resources in total energy consumption were more than 70% in most countries (World Bank, 2011b). This led to 32 teratonnes annual carbon dioxide emission total globally (World Bank, 2011a). The Intergovernmental Panel on Climate Change predicted that the average surface temperature would increase by 1.4 – 5.8 $^{\circ}$C by the end of the 21st century (Zmeureanu & Renaud, 2008). The anthropogenic climate change will cause many problems such as loss of biodiversity and change of the living environment (Abrahamse et al., 2005).

The urgent need for energy conservation is shown as limited energy resources cannot meet the steadily growing demand (Hodgson, 2010). The growing population and the demand for more comfortable living pose great challenges to energy conservation in the residential sector.

Beginning in the early 1980s, many energy conservation programs for detached houses were implemented in the United States, which resulted in an abundant literature on the subject (Burch et al., 1993; Clinton et al., 1986; Goldberg, 1986; Hirst et al., 1989).

A unique phenomenon in the Canadian housing sector was the trend of high-rise multi-unit residential buildings (MURBs) during the Post War times in the Greater Toronto Area (E.R.A. Architects et al., 2010). The old towers degraded over the years. To improve the energy efficiency in the residential sector, those towers face the question: refurbish or replace. The demolition and reconstruction of MURBs is an energy intensive process. Thus, refurbishment is favoured from an environmental perspective. From the financial point of view, refurbishment is much more cost-effective because it can be achieved at 1/2 to 1/5 the cost of demolition and reconstruction of the same number of units (E.R.A. Architects et al., 2010).

It is argued that energy is being used in a wasteful way (Hodgson, 2010). In the residential sector, Meyers et al. (2010) estimated that over 39% of residential primary energy is wasted. Energy consumption can be significantly decreased based on current technology. The potential for energy conservation in the residential sector is very high.

1.2 Overview of the Energy Consumption in Canadian Residential Sector

The residential sector contributes to a significant part of total energy consumption. In Canada, energy used by the residential sector was 17 percent of all secondary energy use. This portion of energy use produced 15 percent of total GHG emissions in 2008 (Natural Resources Canada, 2009). Within this sector, Multi-unit Residential Buildings (MURBs) account for about 24 percent energy use and accommodated approximately 31 percent of Canadians (Liu, 2007). With urbanization, it is inevitable that more MURBs will be built in the cities to sustain a growing urban population.

1.2.1 Toronto Tower Renewal Program

To address the need for energy conservation in high-rise MURBs, the municipal government of Toronto initiated the Toronto Renewal program. This research is supported by the Toronto Tower Renewal program. Part of the analysis will be reported to the program and further research will be done based on the collected data.

Toronto has the second highest density of high-rise buildings in North America (United Way Toronto, 2011). Between 1945 and 1984, more than 1,000 high-rise MURBs of nine or more floors were built (City of Toronto, 2011b). About 800 of the MURBs are privately owned rental properties (City of Toronto, 2011b). MURBs started to thrive during the rapid urbanization of the postwar time. Living in MURBs was considered as a modern life style; thus, was popular among mid-income families (United Way Toronto, 2011).

Decades later, those towers became the new phase of poverty of the city. The buildings are aging and lack maintenance (United Way Toronto, 2011). The neighbourhoods and security of many such MURBs are a cause for concern. It is not an ideal option for comfortable living, but tenants of low socio-economic status have few alternatives (United Way Toronto, 2011).

Despite the issues of these buildings themselves, the occupants of MURBs tend to behave less energy efficiently. Most of these MURBs lack separate meters due to the high cost of installation. Tenants pay a fixed rate for the rent and utilities. Without the knowledge of how much energy has been consumed individually and its cost, tenants are less likely to be eco-friendly (Maruejols & Young, 2011).

From the building owners' perspective, there are not many incentives to improve energy efficiency of their buildings. The payback time period for many retrofits is at least five years (City of Toronto, 2011b). With the increasing energy cost, raising rent would be the easiest way to maintain a financial balance. Current voluntary regulations and retrofit rebate programs are not applicable to existing rental buildings (Natural Resources Canada, 2011); thus, it is difficult to motivate the building owners to voluntarily improve their building energy performance.

To improve the building energy efficiency, the question comes to whether to demolish and rebuild or implement energy conservation programs to the existing MURBs. According to the Leadership in Energy and Environmental Design (LEED®) principles on green buildings, the answer is the latter (Cottrell, 2010). Reusing existing buildings is a vital strategy to reduce waste.

The Toronto Tower Renewal program was designed to allow the MURBs and their neighbourhoods to re-thrive. This would improve quality of life, while minimizing the negative impacts on the environment (City of Toronto, 2011b). In the environmental aspect, it is estimated that the potential in energy reduction can be up to 50 percent of total electricity use and 70 percent of natural gas use (City of Toronto, 2011a) in this type of residential building. This portion is equal to five percent reduction of municipal energy consumption (City of Toronto, 2011a).

1.3 Objective of the Study

This thesis is to investigate the energy consumption in high-rise MURBs in Toronto. Most of these MURBs have the common problems of 1) aging mechanical systems; 2) poor insulation; 3) energy inefficient lighting systems and appliances; 4) inefficient energy management operation, and 5) unavailability of feedback on actual energy use to the occupants.

The Toronto Community Housing Corporation (TCHC) is a partner of the program. TCHC operates over 100 high-rise rental apartment buildings, most of which are social housing. The data required for this research were mostly provided by TCHC. Data for a few buildings were provided by anonymous building owners.

The objectives of this thesis research are four-fold.

1. MURB utility data collection, energy benchmarking methodology procedure development and database establishment. This database is the first weather normalized energy benchmarking for the high-rise MURBs in a single urban area in Canada.

2. Data mining. This thesis investigates the relations between energy efficiency in high-rise MURBs and various factors, including vintage, building gross area, number of unit, and occupancy.

3. Evaluate benchmarking results obtained from the PRInceton Scorekeeping Method (Fels, 1986), simple ratio weather normalization (ASHRAE, 1985) and the ENERGY STAR® Portfolio Manager (Skolnik, 2011). All three methods are widely used in benchmarking practice. However, a comprehensive study and comparison among them is lacking. This research will investigate the discrepancies between the methods. Among the three methods, ENERGY STAR® Portfolio Manager is the most recently developed benchmarking tool. During the time of research, Natural Resources Canada is cooperating with U.S. EPA to introduce the ENERGY STAR® Portfolio Manager to Canada (Natural Resources Canada, 2012b). This research can provide some insight on the Portfolio Manager benchmarking results and evaluate the actual savings from various retrofits implemented on high-rise multi unit residential buildings (MURBs).

4. Identify and quantify the energy savings during the billing period.

1.4 Structure of the Thesis

This thesis is organized into five chapters as outlined with brief contents as follows:

Chapter 1: Introduction on the background to the research and outline of the overall objectives of the study

Chapter 2: Literature review on energy efficiency in MURBs, and energy benchmarking methods

Chapter 3: Proposed weather normalized energy benchmarking and retrofit analysis methods

Chapter 4: Results and discussion on energy benchmarking of high-rise MURBs, possible factors that influence the energy consumption, retrofit assessment, and weather normalization methods comparison

Chapter 5: Conclusion and recommendations

Chapter 2

2 Literature Review

2.1 Background

Canadians have a high demand for energy. In 2009, Canada consumed about 8.5 exajoule of secondary energy[1] (Natural Resources Canada, 2011b). In the 34 countries in the Organisation for Economic Co-operation and Development (OECD), Canada's energy consumption per capita ranks the third highest, after Iceland and Luxembourg (World Bank, 2012a).

In the National Energy Use Database (NEUD) 2009, the residential sector accounted for 17% of total secondary energy (Natural Resources Canada, 2011b). This sector was the third largest energy consumer, after industrial and transportation. Apartments consumed 18% of residential energy. The percentage of energy use in all sectors and sub-categories of the residential sector is shown in Figure 2-1.

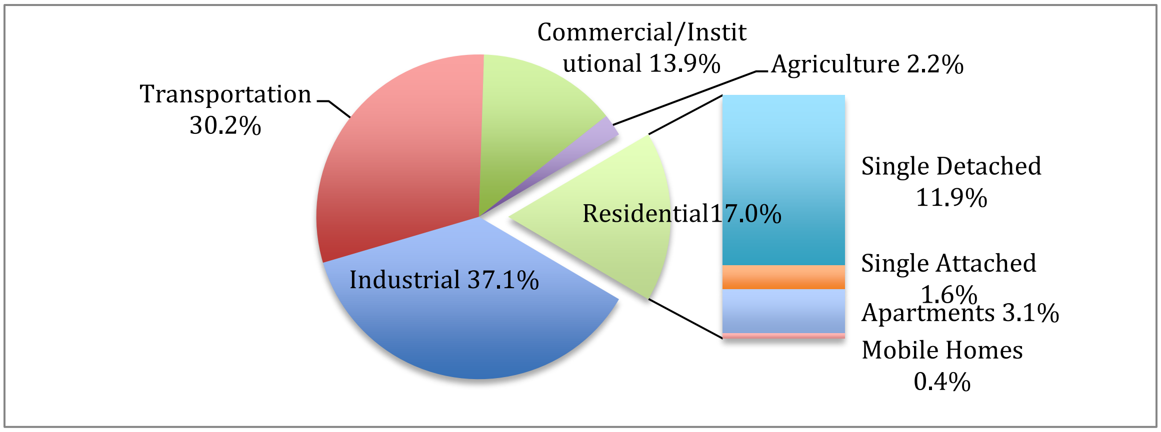

Figure 2-1: Canada secondary energy use by sector, 2009 (Natural Resources Canada, 2011b)

[1] Secondary energy use is the energy used by final consumers for residential, agricultural, commercial, and industrial and transportation purposes.

The residential sector contributes to 15% of total GHG emissions (Natural Resources Canada, 2011b). The GHG emissions by sector are displayed in Figure 2-2.

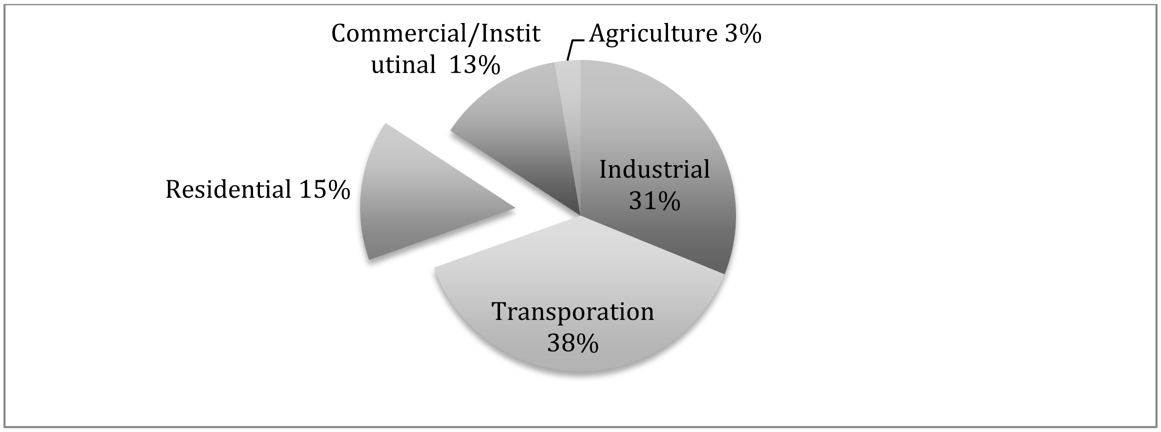

Figure 2-2: Canada GHG emissions by sector, 2009 (Natural Resources Canada, 2011b)

2.2 Energy Intensity in MURBs

The information on energy intensity in MURBs is very limited. Most literature cites data from two Natural Resources Canada databases, the National Energy Use Database (NEUD) and the Survey of Household Energy Use **(**SHEU**).** The two databases use different classifications for each housing type; thus, energy intensities in each household/building type are different, but neither specified the high-rise MURBs. The NEUD classification is based on the household type, while SHEU is based on the building type.

2.2.1 Statistics on Residential Sector in NEUD

The NEUD provides data on domestic energy consumption as well as carbon emissions in residential, transportation, agriculture, industrial, and commercial and institutional sectors (Natural Resources Canada, 2011b). In the NEUD, the “apartments” subcategory in the residential sector is defined by the household type, which comprises broad building types including:

"...dwelling units in apartment blocks or apartment hotels; flats in duplexes or triplexes (i.e. where the division between dwelling units is horizontal); suites in structurally converted houses; living quarters located above or in the rear of stores, restaurants, garages or other business premises; caretakers' quarters in schools, churches, warehouses, etc.; and private quarters for employees in hospitals or other types of institutions."

(Natural Resources Canada, 2011b)

Therefore, apartments surveyed in NEUD are located in various building types including residential buildings and non-residential buildings; the buildings can be high-rise, mid-rise and low-rise. This database provides information on how different household types consume energy, while the factor of the building type is ignored. The findings in NEUD provide an overview of the tenants' type and their household efficiency. This information can be helpful to energy conservation strategies targeting on the occupants. However, for researches on a particular building type, such as high-rise MURBs, the NEUD is not appropriate source.

Even so, the NEUD is still adopted by many researches (Finch et al., 2010). In NEUD, the apartment category is the second largest housing type. The percentage of each household by built type in 2009 is shown in Figure 2-3.

Apartments by household consumed 257PJ of secondary energy, which is 18% of the residential sector in 2009. The percentage of energy consumption for each household type is displayed in Figure 2-4.

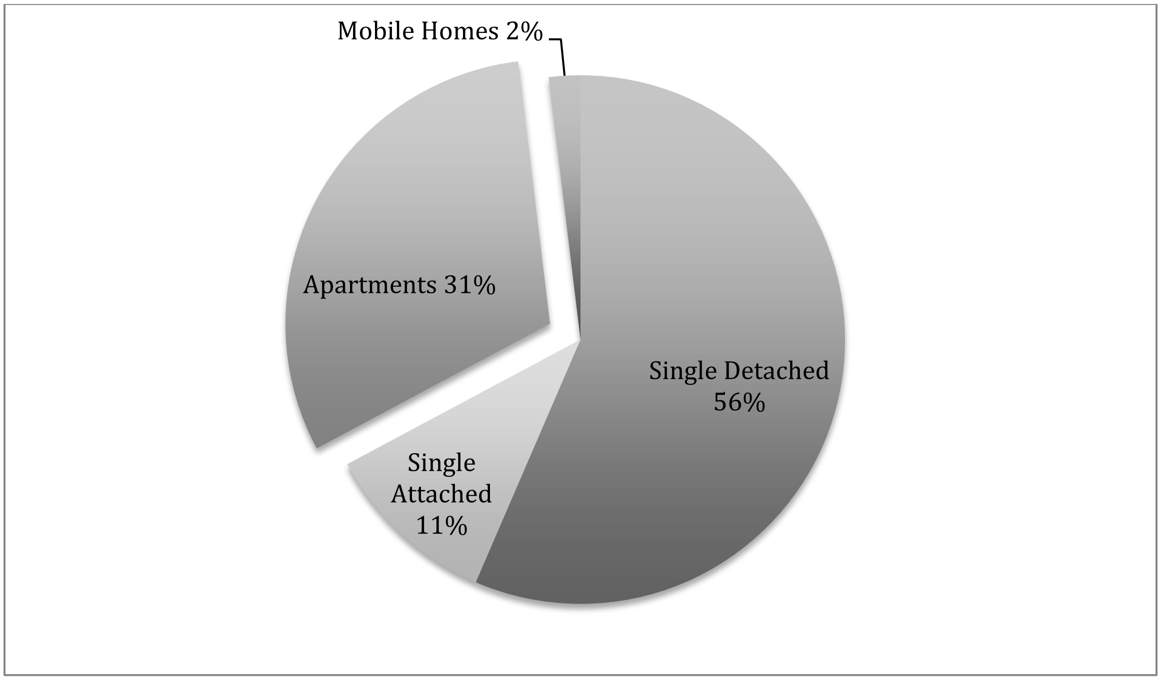

Figure 2-3: Household type Canada, 2009 (Natural Resources Canada, 2011b)

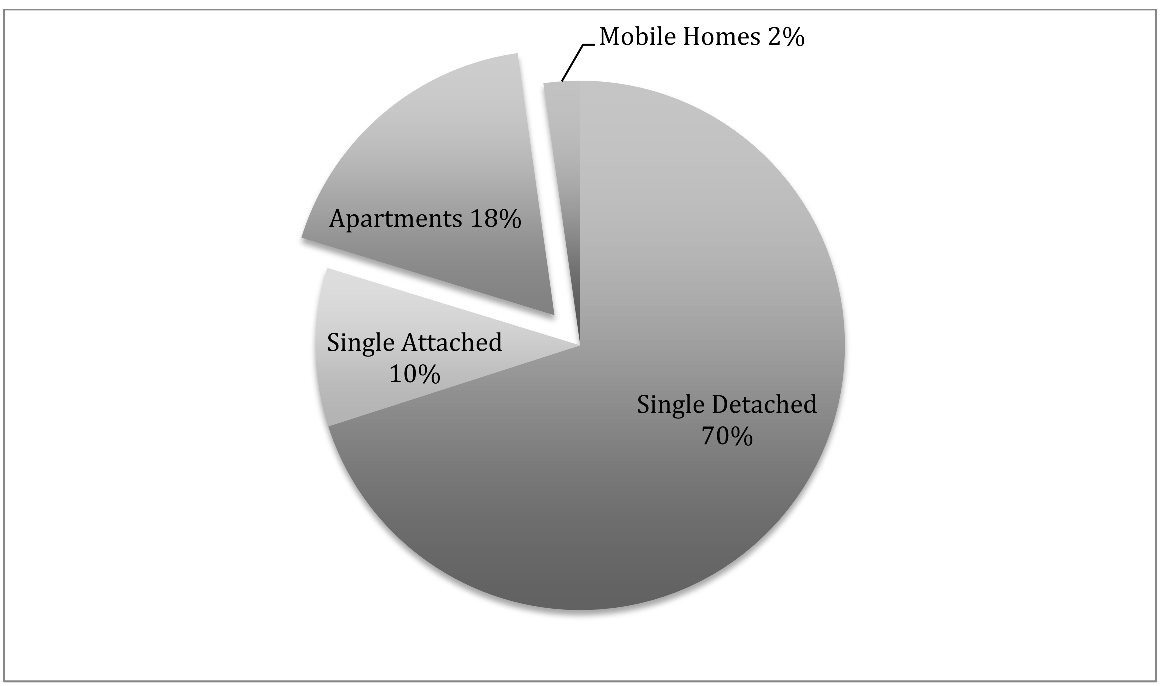

Figure 2-4: Secondary energy use by residential building type, 2009 (Natural Resources Canada, 2011b)

The energy intensity by kWh/m^2 and by household is displayed in figure 2-5. The energy efficiency of the apartment category is the highest compared with single detached, single attached and mobile homes. In terms of per household consumption, apartments represent only half that of single detached houses, and much lower than other household types. This significant difference is due to the average size of apartments being much smaller than single detached houses.

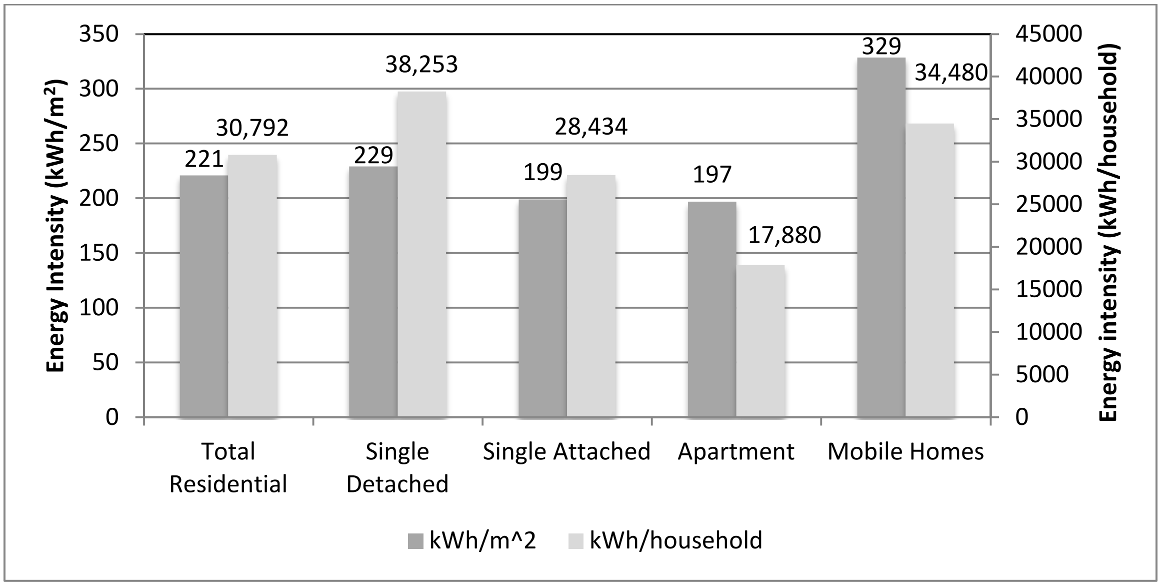

Figure 2-5: Energy intensity by residential household type, 2009 (Natural Resources Canada, 2011b)

2.2.2 Statistics on Residential Sector in SHEU-2007

SHEU was a joint project between Statistics Canada and Natural Resources Canada (Natural Resources Canada, 2010). The database collected information on related information on household energy consumptions. SHEU uses building type for classification, including single detached, double/row houses, apartment and mobile homes. Prior to 2007, data for apartments represent low-rise and mid-rise buildings up to five floors. Beginning in SHEU-2007, buildings with five floors and above are investigated and the corresponding category, the high-rise apartment, was introduced (Natural Resources Canada, 2010)

Figure 2-6 displays the percentage of each dwelling type by build. Nationally, the housing sector is composed of 16.5% low-rise apartments and 8.5% of high-rise apartments. The percentage of high-rise apartments in Ontario is the highest in all provinces, at 16.2% of all dwellings, almost double that of the national level. Statistics for high-rise apartments by province are very limited. Acceptable data are only available for Canada and Ontario. The reliability of data for apartment in other provinces are either unaccepted or should be used with caution, as shown in Figure 2-6.

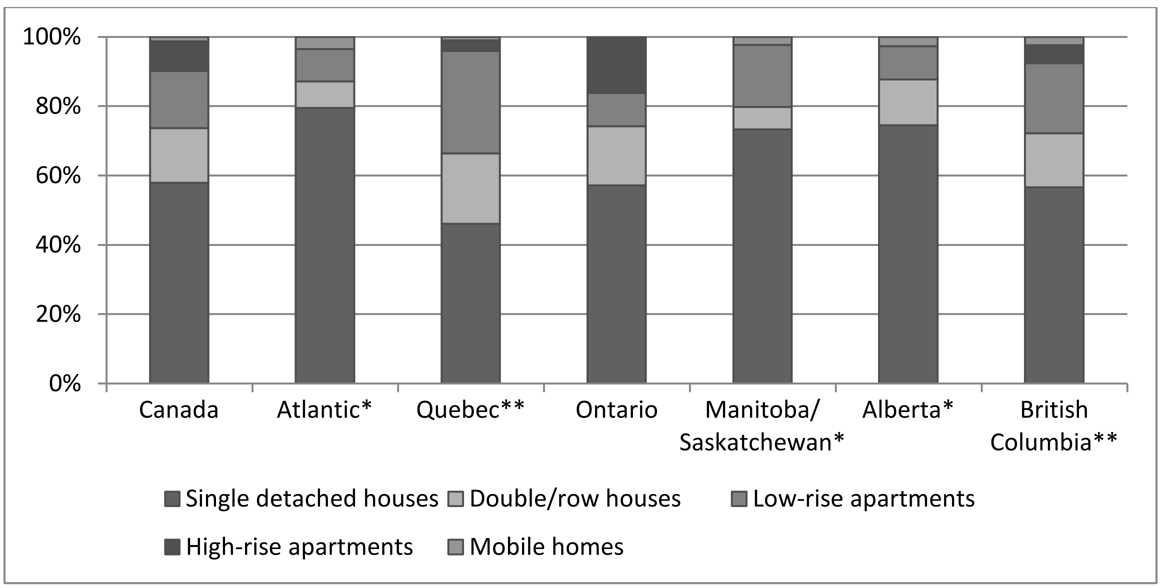

Figure 2-6: Percentage of each dwelling type by built by province, 2007 (Natural Resources Canada, 2010). *use with caution, ** too unreliable to be published

National wide, energy intensity of high-rise apartments is the lowest by square meter and by household as shown in Figure 2-7. The household energy consumption of low-rise and high-rise apartments is only one third of single detached houses and half of double/row houses.

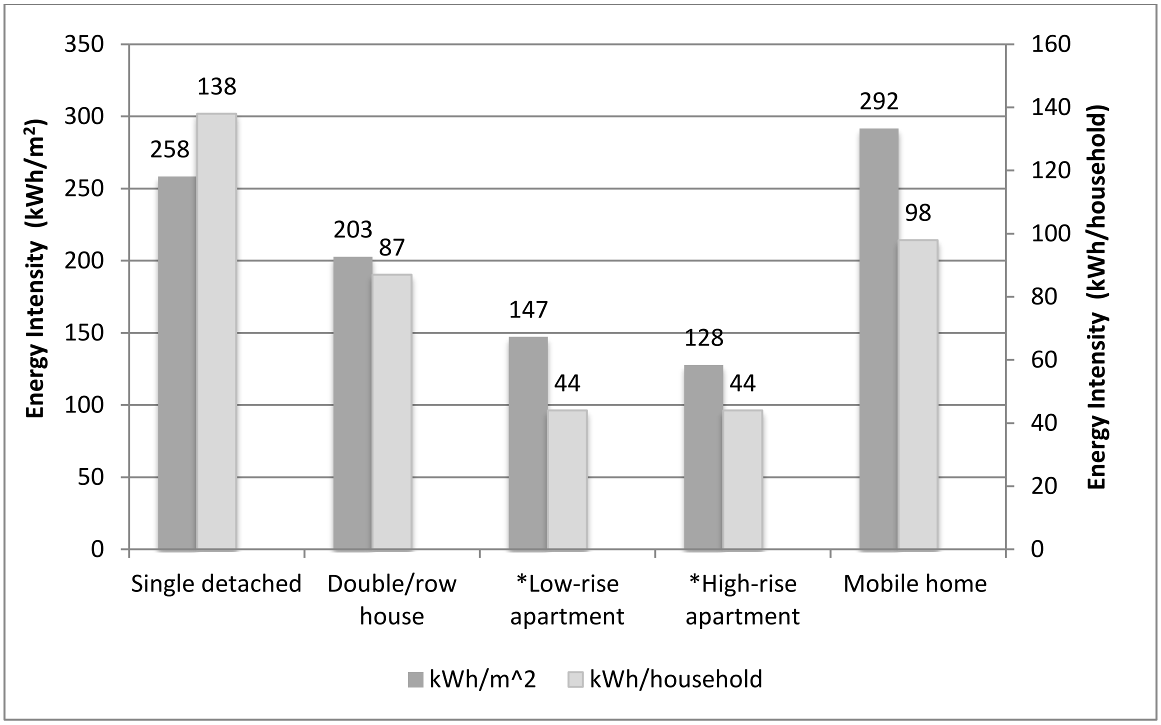

Figure 2-7: Energy intensity by built type, 2007 (Natural Resources Canada, 2010)

The energy intensity of single detached and single attached houses is comparable in NEUD and SHEU-2007. However, the energy intensities per area of both low-rise apartments and high-rise apartments in the SHEU-2007 are much higher than the "apartment" in NEUD. Especially the energy intensity of high-rise apartments is about 30% lower than 'apartment' from NEUD. The discrepancies in the two databases raise the difficulties for the researchers/building owners to compare their building performance with the peers.

Energy intensity varies by locations. Energy consumption per household by region is shown in Figure 2-8. Quebec households have the lowest energy consumption. Quebec uses electricity as the major energy source, which is more efficient than other energy sources (Zmeureanu & Fazio, 1991).

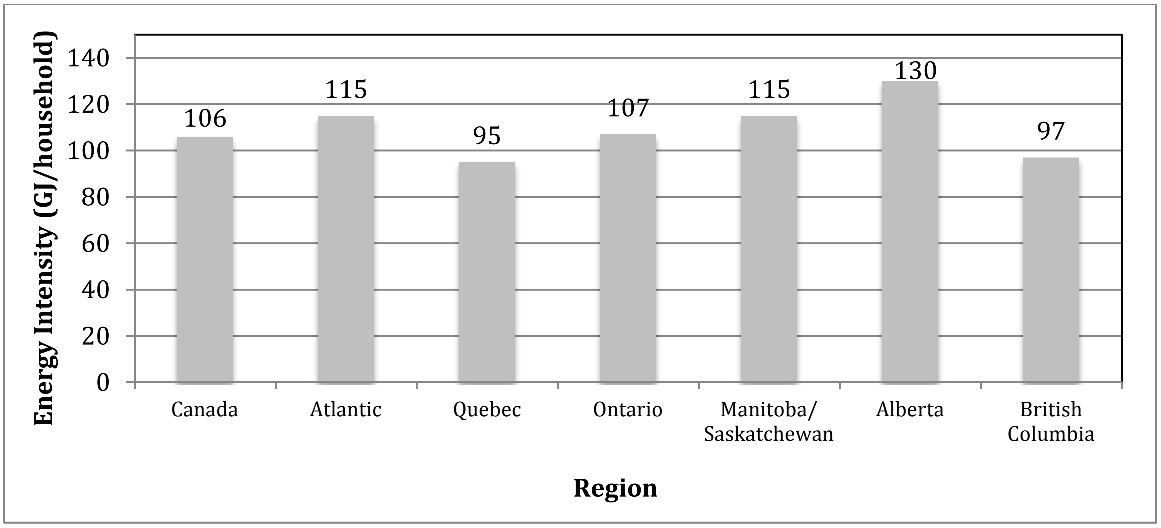

Figure 2-8: Household energy consumption by region, 2007 (Natural Resources Canada, 2010)

Energy intensity is affected by the year of construction. In the residential sector, buildings were usually built to meet the minimum requirement of the building code. Earlier building codes had little consideration for the energy intensity. Therefore towers that were built accordingly have already shown lower energy efficiency than buildings built in more recent times.

As shown in Figure 2-9, the energy consumption per area gradually decreased during the observed time period. Contrary to this trend, the energy consumption per household increased about 10% from 1946 to 1999. This was due to the average household size increasing during the time period.

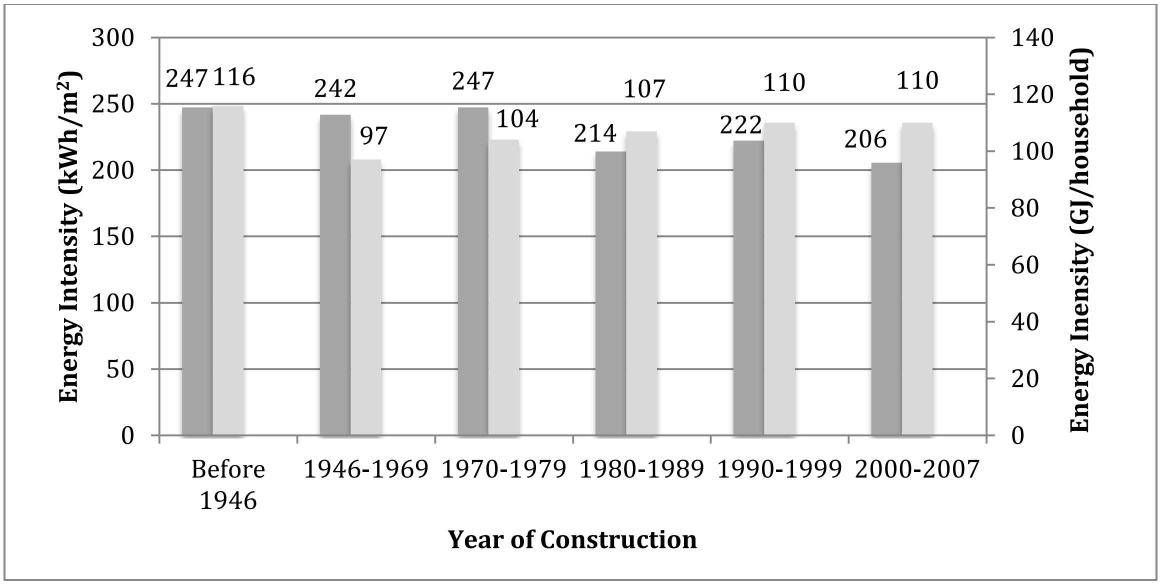

Figure 2-9: Energy consumption by year of construction, 2007 (Natural Resources Canada, 2010)

More than half of the high-rise apartments in the current housing stock were built between 1946 and 1980 as displayed in Figure 2-10. The concern is that in the earlier times, energy intensity was not considered during building design and construction. Moreover, the buildings degraded over the time period, which led to poorer performance.

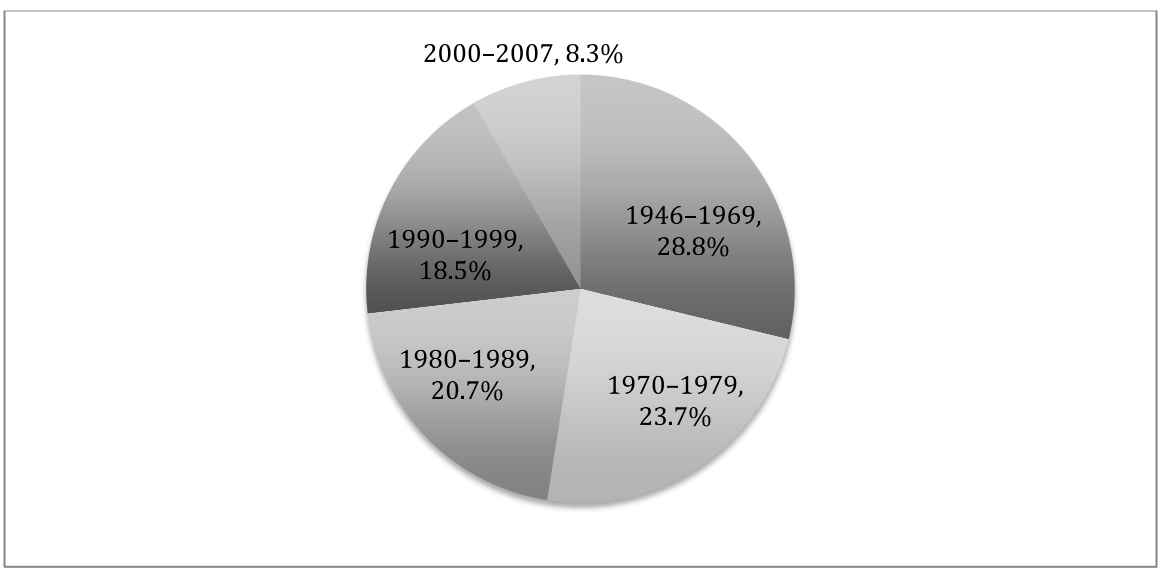

Figure 2-10: Total high-rise apartments housing stock by vintage Ontario, 2007 (Natural Resources Canada, 2010)

2.2.3 Other Researches on Canadian MURBs

Research on energy intensity has been done one a small scale in Canada. The MURBs studied were from mid-rise to high-rise, including single, family and senior occupancy type and located in the single province/area and across Canada. The energy intensity of MURBs in different studies is within a comparable range; however, are all much higher than data from NEUD and SHEU-2007, some as much as double. The results from some selected research are shown in Table 2-1.

Canada Mortgage and Housing Corporation (CMHC) has conducted research on 40 apartment buildings across Canada (Enermodal Engineering Limited, 2001). These 40 buildings studied had a mean energy intensity of 279 kWh/m^2. Buildings built after 1981 showed a 50% higher consumption compared with buildings built between 1961 and 1980. Buildings occupied by seniors consumed much more energy than buildings occupied by singles and families. A major drawback of the CHMC HISTAR database is that the number of sample buildings is not large enough to be representative.

Another study from CMHC examined 10 high-rise MURBs across Canada, including two buildings located in each of the following provinces: Newfoundland, Ontario, Manitoba, Quebec and British Columbia. The study found energy intensity ranged from 152 to 309 kWh/m^2, normalized to weather (Scanada Consultants Limited, 1997).

Eighty-eight Ontario Housing Corporation (OHC) high-rise apartments were assessed. Two-thirds of the buildings had energy intensity ranging from 150 to 250 kWh/m^2 with a mean of 232 kWh/m^2 (Canada Mortage and Housing Corporation, 2007). An interesting finding of this research is that apartment buildings located in Toronto have greater energy usage than buildings in colder locations. The study explained that the greater portion of family-type buildings might use more energy than buildings with other occupancy types.

Finch et al (2010) developed a baseline of 39 mid-rise to high-rise MURBs in the Lower Mainland and Victoria BC. Energy intensity ranged from 144 to 299 kWh/m^2, with an average of 213 kWh/m^2 and a median of 217 kWh/m^2. The average heating degree-day (HDD)[2] based on 18˚C is 2712 for the studied period. The climate in BC is milder compared with other provinces; thus requires less energy for space heating related demands. Another possible reason is that BC uses higher percentage electricity for heating (Natural Resources Canada, 2010). In 2007, electricity was 34% of the principal energy source for heating in BC, while it was 20% in Ontario. This can contribute to a relatively low energy consumption of the buildings comparing with buildings located in other regions.

Maruejols and Young (2010) found that whoever pays utility bills has a great impact on energy use. In their study based on SHEU 2003, MURBs in low-rise apartment buildings used 70% more electricity and 114% more overall energy when landlords paid for the utilities. MURBs in row houses and detached houses showed fewer differences but still used 40% more electricity and 37% more overall energy when landlords paid for the utilities. Levinson and Niemann (2004) had similar findings from the Residential Energy Consumption Survey and the American Housing Survey. They argued that although sub-metering can be one of the most cost-effective energy conservation measures, obstacles such as the installation fees, slow adoption of cost-effective residential energy-conservation technologies, and rental contracts with zero-marginal-cost energy use elevated the energy consumption in rental housing when landlords paid for the utilities.

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[2] The term HDD is further discussed in Section 2.6.

Table 2.1: Energy intensity of high-rise MURBs in studies

Source	Building Location	Billing Year	Year of Built	Occupancy Type	Number of Buildings	*Energy Intensity (kWh/m^2)
(Enermodal Engineering Limited, 2001)	Across Canada	-	1920 - 1993	Single, Seniors & Families	40	279
	Across Canada	-	1981 - 1993	-	9	212
	Across Canada	-	1961 - 1980	-	26	317
	Across Canada	-	-	Singles	2	221
	Across Canada	-	-	Seniors	13	281
	Across Canada	-	-	Families	2	163
Scanada Consultants Limited, 2001	Across Canada	Sep./Oct. 1994 – May/June 1995	1960 - 1991	N/A	10	152 – 309 (Weather normalized)
(Canada Mortage and Housing Corporation, 2007)	Ontario	-	1960 - 1989	Family and Seniors	88	232
Finch et al. 2010	Lower Mainland and Victoria, BC	Aug./2003 – June 2005	1974 – 2002	-	39	Mean: 213 Range: 144 – 299

*The energy intensities obtained from the listed references are the actual consumption, unless notified.

2.2.4 The Gap in Current Available Data

The majorities of the energy intensities reported in the previously listed database is not normalized to a common base; thus, these figures only give the general energy consumption pattern. Both NUED and SHEU-2007 data are based on general classifications of the residential sector. Factors such as locations, year of construction, occupancy type, demographics and many more have a great influence on the energy consumption, and cannot be merged into one category. The fact that there is no information specified on the high-rise MURBs impedes the promoting, planning and regulating of energy conservation in the sector.

Although some researches have reported energy intensity of high-rise MURBs, the methodologies used were not uniform. As a result, the energy intensities from various sources do not provide actual differences of the building performance and are inappropriate for scientific comparison. It is necessary to develop a benchmarking tool that can evaluate the actual building energy performance and can be applied to nationwide.

2.3 Why Conserve Energy?

Energy conservation is to use less energy to satisfy the same level of need. The savings can be secondary energy or any related parameter, such as primary energy, CO_2 emissions or energy costs without compromising comfort, health and productivity level (Perez-Lombard et al., 2009).

The use of energy allows humans to maintain a quality of living. Human beings started using energy in the form of fire in the prehistoric times, and expanded to the use of energy in almost every aspect of life. Displayed in Figure 2-11, substantial increases in energy use began in the industrial times as a result of the increase in productivity.

The energy supply was taken for granted until the shocking wake-up call during the 1970s, the Oil Crisis. It was then later found that the fossil fuels by nature are limited. Consequently, the concept of sustainability emerged. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). To achieve sustainability, energy conservation is one major strategy.

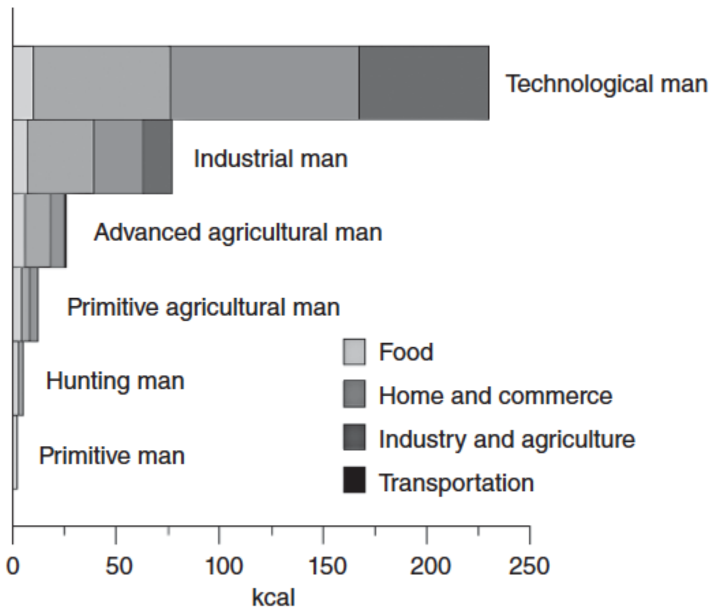

Figure 2-11: Estimated energy consumption per capita per day over the ages, data from (Christian Ngo and Natowitz, 2009), cited from E. Cook, Scientific American, 1971

Energy conservation is urged not only by limited supply, but also by environmental concerns. Current energy supply still heavily depends on non-renewable sources. For example, in 2010, about 75% of energy supply in Canada was from fossil fuel (World Bank, 2012b). The direct problem resulting from use of fossil fuel is the green house gas emissions (GHGs), which elevate the seriousness of anthropogenic global warming and further lead to the degradation of ecosystems, loss of diversity etc.

The increase of population exacerbates the total energy demand. U.S. Census Bureau (USCB) estimated the population of the earth reached 7 billion in 2012 and projected an increase of 1 billion in the next decade. The world population projections from 1950 to 2050 are displayed in Figure 2-12.

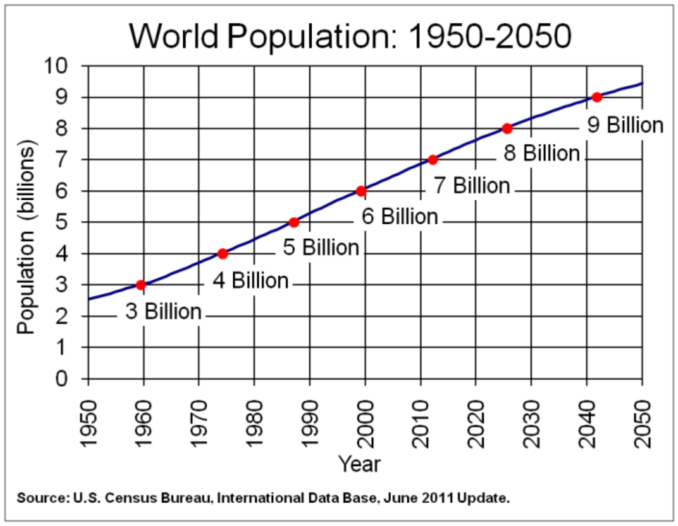

Figure 2-12: World Population Projections 1950 – 2050 (United States Census Bureau, 2011)

How to meet the need of the 7 billion people and even more in the future is challenging to the current available resources on the planet. All human beings have a need for housing. Therefore, reducing energy consumption in the residential sector can be one of the most effective and widely used strategies to achieve energy conservation and sustainable future.

2.4 What is Energy Benchmarking?

The word "benchmark" was originally used in topography, defined as a mark on a permanent object indicating elevation and serving as a reference in topographic survey and tidal observation (Perez-Lombard et al., 2009). Started in 1990s, the term was used in the building sector, referring to the comparison of energy use in buildings with similar characteristics (Nikolaou et al., 2011). Mcdonald and Livegood (2000) described energy benchmarking as an initial energy performance assessment without rigorous evaluation.

The purpose of benchmarking energy consumption is to promote efficient use of energy. Knowing that the energy used by a building is excessive is the first step to make positive changes (MacDonald & Livengood, 2000). By developing a benchmarking tool, one can estimate energy consumption of similar buildings and determine if a sample building is more efficient than other similar buildings (Chung, 2011). Based on the benchmark, building owners can obtain an overview of the energy intensity of their building and compare that with its peers, so that to decide if a retrofit is necessary. Based on an energy benchmark, one can estimate the potential in energy and cost to expect saving when pursuing better performance. From the social point of view, owners of less efficient buildings may face public criticism, which could compel them to take actions to upgrade.

Performing energy benchmarking is necessary before any major retrofit implementation. The pre-retrofit benchmark is a baseline for energy conservation programs. The effectiveness of a retrofit program can be evaluated by comparing energy consumption before and after the retrofit through a consistent method.

Little regulation and certification are available within the existing high-rise MURBs. A major obstacle is that little has been known about the energy intensity of the sector. For policy makers, the benchmark of existing high-rise MURBs provides a realistic goal for setting building energy efficiency standards. Benchmarks of a significant number of buildings with similar high-rise MURBs are urgently needed to be representative for the housing stock. Robust and accurate models are essential during the baseline process and also to develop effective policies. For the future use, the same benchmarking methods should be used to determine if the buildings meet the regulations and certification requirements.

2.5 Benchmarking Methods Overview

Energy benchmarking methods can be either top-down or bottom-up (C. Bohringer & Rutherford, 2008). The bottom-up methods evaluate energy consumption on disaggregated level while top-down methods on aggregated level (Kavgic et al., 2010). Depending on the methods, the input data require information such as the physical characteristics of the dwellings, occupants and their appliances, historical energy consumption, climatic conditions, and macroeconomic indicators (Swan & Ugursal, 2009).

The bottom-up methods look at various related components to estimate their individual impact on energy usage. Bottom-up methods provide information on how energy is used in the building for different purposes. The breakdown information on end-use is valuable when targeting energy saving goals.

The bottom-up methods can be based on statistical data or building physics (Kavgic et al., 2010). Both require comprehensive database of empirical data for each disaggregated component (Kavgic et al, 2010). The bottom-up statistical methods usually rely on monthly billing data and information on all energy end-uses. The end-use by different components can be achieved using survey and/or sub-metering (Wilson & Swisher, 1993).

SHEU-2007 is an example of using surveys to obtain energy end-use in homes. SHEU-2007 conducted surveys on tenants' demographics, appliances possessed and schedule of use. The drawback of bottom-up statistical methods is that the responses are subjective, which can be discrepant from actual use. The methods are also limited in their capacity to quantify energy conservation measures (Kavgic et al., 2010).

Installing sub-meters for various loads in homes can provide quantified information. The empirical data would be very helpful to assist with developing building simulation models. However, the high cost on installation determines that very few tenants/building owners are interested in the investment. The cost is also a burden for researchers who would like to examine a large sample group.

One of the beneficial results associated with installing sub-meters is that giving occupants' feedback on energy consumption can alter their habits and reduce energy end-use. Ehrhardt-Martinez et al. (2010) evaluated various feedback programs and found that 4-12% electricity savings were achieved through the feedback program.

The bottom-up building physics methods require high expertise. One example of the methods is the Canadian Residential Energy End-use Model (CREEM). CREEM was used to evaluate energy consumption in single-detached, semi-attached, row and duplex houses. CREEM uses HOT2000 to estimate the break-down of end-uses including space heating, domestic hot water, appliances & lighting (Farahbakhsh et al., 1998). This model is capable of evaluating impact on energy use and carbon emissions in a wide range of retrofit and upgrade scenarios (Farahbakhsh et al., 1998). The drawback of the CREEM is its limitation on applicable house types due to lack of empirical data for high-rise and low-rise MURBs (Fung et al., 2000).

In general, bottom-up methods can estimate prospective technologies in detail in order to meet saving target, but possibly discrepant from the actual use due to the assumptions made on occupants' behaviours. Without knowledge of the influences from tenants, total energy demand can be 15-20% different from predicted (Olofsson et al., 1998).

The top-down methods looking at buildings as a whole; thus, require little detail of the actual consumption processes (Swan & Ugursal, 2009). Input data are relatively simple compared with bottom-up methods. Many top-down benchmarking methods can be based on total utility bills and single or multiple measures. The historical bills can reflect the factor of random occupant behaviour. The outdoor dry-bulb temperature is widely used as the single measure. Multiple measures varies depend on the research. The multiple measures can be temperature parameters and/or building characteristics. For example, Reddy and Claridge (1994) used multiple measured including outdoor dry-bulb temperature, humidity and horizontal solar radiation to model building energy use. Yalcintas (2006) used plug load, lighting, and HVAC input as the multiple measures in the energy benchmarking.

The down side of using historical consumption information is that it does not necessary predict future trends, especially under recent noticeable changing climate and technology updates. Moreover, general information used for top-down analysis is not sufficient to provide possible retrofit strategies (Perez-Lombard et al., 2009).

2.6 Benchmarking Methods Selection

To develop a benchmarking strategy for high-rise MURBs, a statistically significant number of buildings should be included in the database. In order to collect enough data, ideal methods should be based on easily acquired information to encourage building owner/property management participation. Given the massive amount of data involved, simple tools are desired for a cost effective evaluation process. This study will focus on single measure top-down methods of benchmarking.

The residential energy use is influenced by multiple factors; including building physics, operation, tenants' characteristics, and natural conditions. Among these factors, climate has been identified as the major variable for energy use in cold climate region (Fels, 1986, ASHRAE 1985).

When space heating is needed in the winter, the simplest method to estimate energy consumption is to assume that the energy required to maintain comfort is a function of a single parameter, the outdoor dry-bulb temperature (ASHRAE, 1985). The dry-bulb temperature is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture (Nall, 2004). Nall claimed that the dry-bulb temperature is the most important climate variables for human comfort and building energy efficiency (Nall, 2004). The energy consumption normalized by weather variable is based on the assumption that when outdoor temperature drops below a certain level, a constant amount of heating fuel is required for each additional degree of temperature drop (Chung, 2011).

The term heating degree-days is used as an indicator of building heating needs. Heating and cooling degree-days are calculated as the sum of the difference between daily the reference temperature and outdoor temperature (ASHRAE, 2009). The reference temperature for a building is the temperature at which neither heating nor cooling is needed. It is determined by building characteristics, tenants' behaviours and appliances (Rachlin et al., 1986). Although reference temperature differs from building to building, this temperature is commonly accepted as either 50 or 65°F (10 or 18.3˚C) (ASHRAE, 2009). Environment Canada (2011b) defines HDD as "the annual sum of degrees of the average daily temperature for all days below 18˚C.

Canada is a typical cold climate country (Natural Resources Canada, 2011a). Based on the HDD, Canada can be divided into four climate zones. Toronto is located in zone B on Figure 2-13, with a HDD between 3500 to 5500 range (Natural Resources Canada, 2011a).

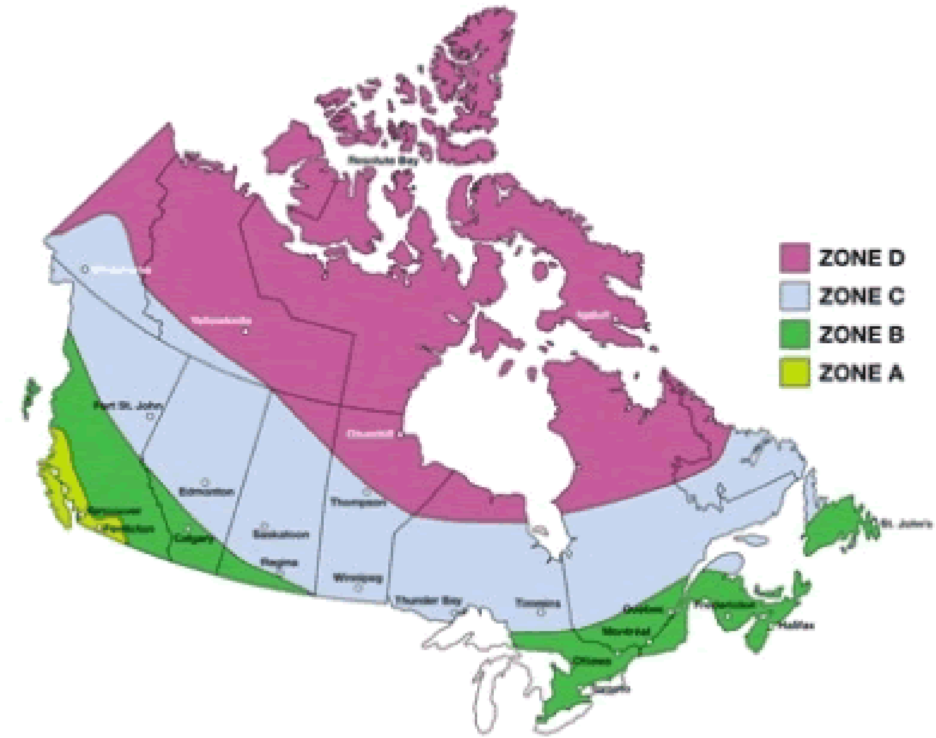

Figure 2-13: Map of Canada's climate zones (Natural Resources Canada, 2011a).. Zone A: <- 3500 HDDs, Zone B: > 3500 to <= 5500, Zone > 5500 <= 8000, Zone D > 8000

A typical energy consumption pattern in a cold climate is that a large portion of energy is used for space heating. In 2009, 63% of secondary energy in the Canadian residential sector was used for space heating. As shown in Figure 14, the non-weather related consumption including lighting and appliances is less than 20% of residential secondary energy use (Natural Resources Canada, 2012a).

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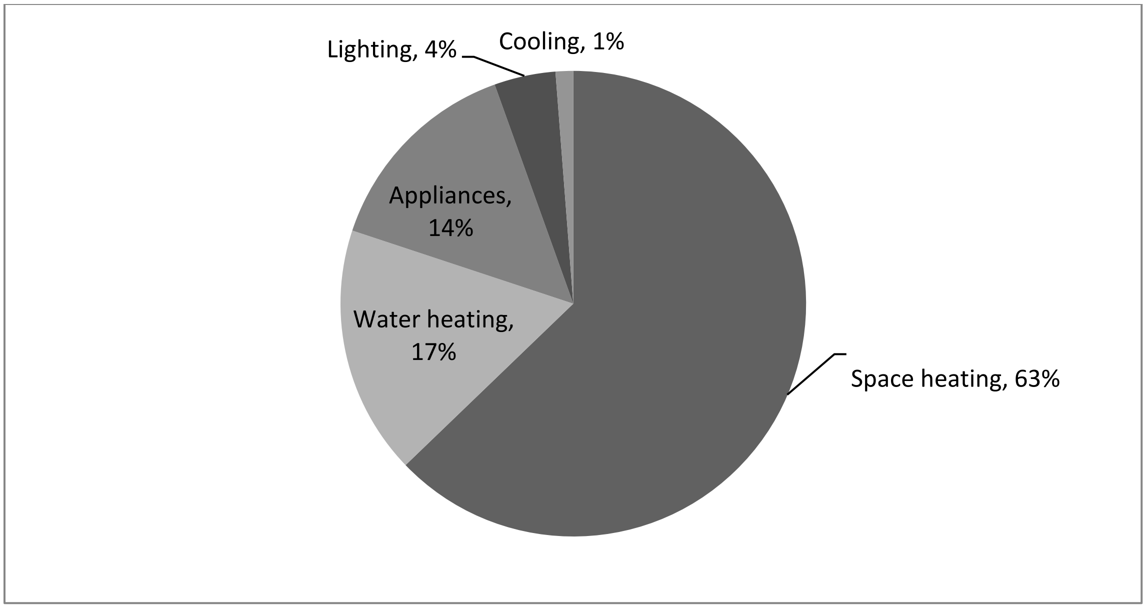

Figure 2-14: Residential secondary energy use (Natural Resources Canada, 2012a)

Building energy consumption estimated using outdoor dry-bulb temperature is called weather normalization. Weather normalization methods are widely used in building energy benchmarking in cold climates. The weather normalization is based on the assumption that energy consumption for space heating follows a linear relation to the difference of the indoor and outdoor temperature, namely HDD and the other end-use is constant over the year (Fels, 1986). Hirst & Goeltz indicated that outdoor temperature has the greatest short-term influence on fluctuations in household energy consumption while factors such as changes in fuel prices, household income, the number of household members affect energy use only in the longer term (Hirst & Goeltz, 1986).

Some widely used energy benchmarking tools are developed using the weather normalization concept. This research will review the ASHRAE simple ratio weather normalization (SRWN) method (ASHRAE, 1985) and ENERGY STAR® Portfolio Manager

(U.S. Environmental Protection Agency, 2011a) compared with Princeton Scorekeeping Method (PRISM) (Fels, 1986).

2.6.1 PRInceton Scorekeeping Method

PRISM was designed by Princeton University in 1984 (Fels, 1986) to measure the effectiveness of government/authority funded residential conservation programs. PRISM was applied and validated by housing types, from single detached houses to mid-rise MURBs and by fuel type, including natural gas, oil and electricity. PRISM produced satisfactory results when proper data were available (Goeltz & Hirst, 1987).

PRISM is a regression-based model for the evaluation of household energy consumption (Fels, 1986). PRISM uses two variables, outdoor temperature and energy consumption, in the regression model to establish a base load, heating slope and reference temperature (Fels, 1986). The PRISM assumes that household energy consumption consists of a non-weather related base load and a weather related space heating (Kavgic et al., 2010). Necessary data inputs are monthly energy consumption, which is reflected by utility bills, and weather information obtained from a nearby weather station. The result of this analysis is normalized annual consumption (NAC). The NAC represents the total energy consumption of the building under a typical weather conditions for the location. The NAC makes it possible for a building to compare its energy consumption in different years and in different weather conditions.

PRISM assumes that the energy consumption base load remains the same for the whole year. The base load includes lighting, appliances and domestic hot water. The impact of seasonality, with regard to non-heating consumption, is ignored. The highest non-heating consumption occurs in winter, which is caused by increased demands in water heating, cooking, lights, dryers. The non-heating energy consumption between winter season and summer season can be up to 20 percent in the studied houses (Fels et al., 1986). Those changes are associated with seasonal changes similar to space heating and cooling (Fels et al., 1986). Thus, the non-heating consumption systematically adds onto the space heating/cooling loads (Fels et al., 1986)

PRISM models output three parameters: base load consumption, heating and/or cooling slope and reference temperature (Fels, 1986). These three parameters determines the energy use of the studied object, and is called the energy signature (Yu & Chow, 2007).

One of the highlights in PRISM is that the method calculates a reference temperature to achieve the optimized linear regression (Fels, 1986). In the PRISM model, the reference temperature obtained from a statistical approach incorporated the factors that influence the heat balance in the building. These factors include but are not limited to the building envelope, HVAC system and operation, the density of the building, and appliances in the building. Therefore, the optimized reference temperature is a characteristic of the building (Finch et al., 2010). The higher reference temperature in heating dominated buildings compared with their peers, indicate that these buildings require space heating at a higher outdoor temperature. The reference temperature can be set to a fixed temperature (Fels, 1986) in PRISM. This is useful if the building operators know the temperature of which they turn on the central heating or cooling system.

The energy signature of a typical house in a cold climate is displayed in Figure 2-15.

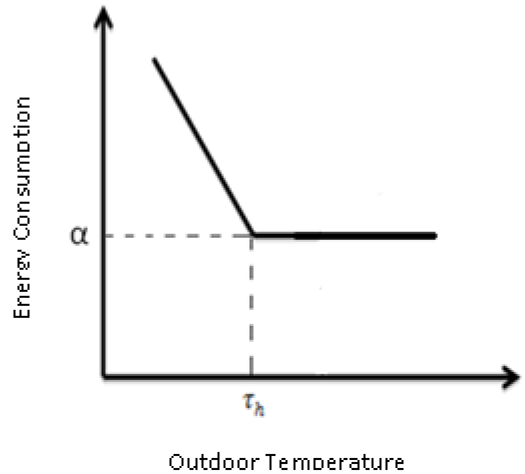

Figure 2-15: PRISM heating only model

This assumption is applied and validated in many actual houses (Goldberg, 1986; Hirst & Goeltz, 1986; Hwang, 1989; Rachlin et al., 1986). Hirst & Goeltz (1986) investigated 71 electric heated single detached houses which were monitored for space heating, water heating and indoor temperature at 15-minute intervals. They found that the PRISM-estimated total annual electricity consumption correlates with the actual use: the maximum discrepancy between PRISM estimates and the measured consumption is less than 1%. They also found that the space heating electricity use is 6% higher and base load use is 3% lower than the monitored. A possible reason for the differences between the PRISM model and actual consumption is due to seasonality. This phenomenon can be explained by the different energy use schedule during heating seasons and non-heating seasons. In cold climates, people tend to spend more time indoors in the winter and less time during the summer. This is a minor misallocation of different end-uses due to the seasonal effect. PRISM uses consumption in the non-heating season as base load; thus it is underestimated. PRISM estimated space heating energy use includes energy needed for space heating and increased indoor activity time. As a result, the estimates for space heating are likely to be slightly higher than the actual use.

The energy signature for energy consumption in hot summer and warm winter climates is shown in Figure 2-16. The correlation between energy use and outdoor temperature and/or cooling degree-days (CDD)[3] is not as reliable as in the heating related consumptions. The demand for cooling is not just determined by the outdoor temperature. Yalcintas (2008) found that if dew point temperature is considered, the estimation of cooling demand improved.

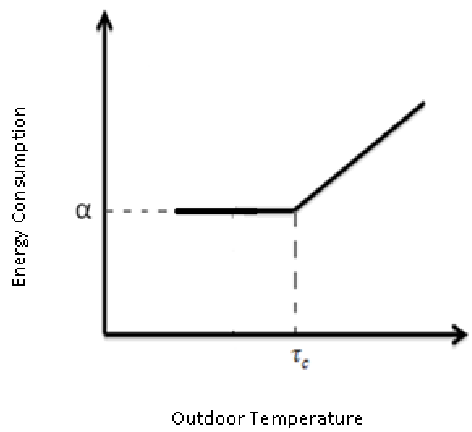

Figure 2-16: PRISM cooling only model

In heating only and cooling only models, PRISM incorporates a robust function. When an outlier detected, the operator can require PRISM run robust model. Under robust model, PRISM automatically assigns a lower weight to the outlier to generate an adjusted reading. The adjusted reading then will be used for NAC calculation. This is to increase the usefulness of the billing data while maintain the reliability of the linear regression model (Fels, 1986).

In Canada, buildings require a significant amount of energy for space heating, and some households require small amount energy for cooling in the summer. This type of energy signature is displayed in Figure 2-17. The use of cooling in the summer can be observed on the

[3] The term CDD is further discussed in Section 2.6.

utility bills. The readings in the summer month(s), form a peak compared with spring and fall (Stram & Fels, 1986).

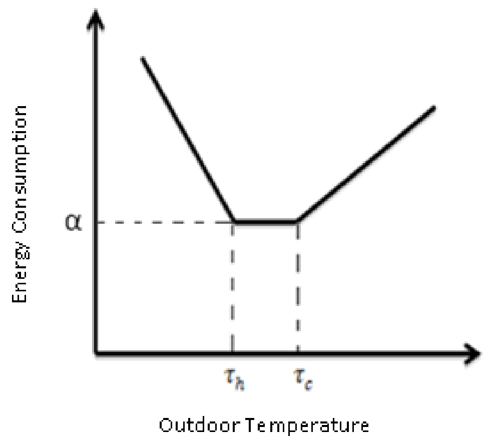

Figure 2-17: PRISM heating and cooling model

The daily base load consumption (α) remains constant when outdoor temperature (T_{out}) is above the heating reference temperate (τ_h) heating and below the cooling reference temperature (τ_c). In the heating seasons, when the outdoor temperature drops below the reference temperature, the energy consumption increases linearly to compensate the heat loss. The slope of the change in energy consumption, the heating slope (β_h) is equal to the heat-loss rate of the house. The heating slope represent the amount of energy needed for a given temperature drop. An energy efficient house will have a small heating slope. Similarly, the cooling slope (β_c) is equal to the heat-gain rate of the house.

Thus, normalized annual consumption (NAC), is given by

$$NAC = 365\alpha + \delta_h \beta_h H_o(\tau_h) + \delta_c \beta_c C_o(\tau_c) \qquad (2\text{-}1)$$

Where,

δ_h = 1 for the HO and HC model, otherwise zero

δ_c = 1 for the CO and HC model, otherwise zero

$H_o(\tau_h)$ = long-term average heating degree-days per year to the PRISM estimated reference temperature τ_h

$C_o(\tau_c)$ = long-term average cooling degree-days per year to the PRISM estimated reference temperature τ_c

Stram & Fels (1986) studied cooling and heating required houses located in New Jersey. They found that some houses showed electric cooling consumption from zero to up to 2 months. The cooling reference temperature is well above the heating reference temperature, in the range of 21-29˚C. They also found that in those households, the variable of tenants' behaviour plays an important role in electric cooling consumption and this decision is not solely determined by outdoor temperature. Therefore, a high level of accuracy for the cooling parameters may not be acquired. Even so, Stram & Fels (1986) argued that for houses with a substantial demand for space-heating and small amount for cooling, PRISM in general provides a reliable NAC.

PRISM has been successfully applied to single houses and MURBs, heated by gas and electricity in different weather conditions (Decicco et al., 1986; Hirst, 1986). An exception happened in a research project on detached and row houses in New York City using oil for space heating source (Rodberg, 1986). This anomaly may have been caused by the long intervals between deliveries (Fels et al, 1986b) or by financial limitations when purchasing heating oil.

For optimal and reliable analysis, a 12-month consecutive billing record is required (Fels, 1986; Hirst & Goeltz, 1986). Hirst & Goltez found that using bills only from the winter would overestimate the NAC while only using bills for summer season would underestimate the NAC.

They also found that using Spring/Fall bills can obtain a NAC approximately equal to the one using full year.

Six bi-monthly bills can be an alternative of 12 monthly readings, but missing one piece of data could be troublesome. Results from fewer than ten consecutive months or missing three months of one year may lead to unacceptable inaccuracies; thus, they need to be carefully scrutinized (Rachlin et al, 1986).

Past research has shown that the majority of billing records provided by occupants was incomplete and was deleted from further analysis (Rodberg, 1986). A billing history obtained directly from energy suppliers is most reliable, but this involves questions about confidentiality issues that may result in a low participation rate. MURBs operated by management companies are the ideal targets as they usually keep relatively complete records of utility bills (Fels & Reynolds, 1992). Moreover, when looking at a MURB as one user, the variations in tenants behaviour as an aggregate is less likely to impact the total building consumption substantially. The Hood River Conservation project selected 320 houses, but found that only 148 houses were eligible (Hwang, 1989). The ineligible cases were either missing utility data, or tenants were away for vacations result in discontinues energy consumption.

The PRISM is an effective and reliable benchmarking tool for describing historical energy consumption. It can provide an estimation of the direct actual energy savings after a retrofit program. PRISM cannot predict future energy use nor provide accurate breakdown of energy uses. Additional simulations are needed for the above purposes.

2.6.2 Simple Ratio Weather Normalization Method

Similar to PRISM, the simple ratio weather normalization (SRWN) methods use the traditional degree-day procedure for estimating heating energy requirements. In heating dominated climate, this method is used to estimate the total energy consumption. The demand for cooling is ignored in SRWN.

SRWN simplifies the estimation process by assuming the reference temperature is 18.3˚C. The estimated energy consumption is calculated using Equation 2-2 (ASHRAE, 1985).

$$E = \frac{E_a}{HDD_a} \times HDD_L \qquad (2\text{-}2)$$

Where:

E : Normalized annual energy consumption

E_a: Actual energy consumption

HDD_a : Actual HDD of the billing period

HDD_L : Long-term annual HDD

The SRWN is a simple benchmarking tool that has been used industry for decades.

2.6.3 ENERGY STAR® Portfolio Manager

The EPA has introduced an online energy management tool, the ENERGY STAR® Portfolio Manager (PM), used to assess energy consumptions (U.S. Environmental Protection Agency, n.d.-a). At the time of this research, Natural Resources Canada is in the process of launching the PM in Canada (Natural Resources Canada, 2012b). By inputting monthly utility consumptions, location of the building, and required building specifications, the PM can provide the weather-normalized energy benchmarking for a building. The PM can also provide an energy performance scale according to the ENERGY STAR® standard.

ENERGY STAR® is a voluntary government/industry consortium that provides information on energy-efficient solutions to businesses and consumers (Boyd et al., 2008). ENERGY STAR® energy performance labels have been widely used in many areas, such as home appliances, commercial buildings, schools, hospitals, industries etc. In the residential sector, the ENERGY STAR® energy performance scale is based on existing buildings. The energy efficiency ratios of existing buildings from survey data were used to create a distribution of energy performance. The ENERGY STAR® 1 to 100 performance scale follows a percentage point system (U.S. Environmental Protection Agency, n.d.-a). ENERGY STAR® energy performance scale is indirectly related to energy codes, as the buildings represents the energy code at construction (U.S. Environmental Protection Agency, n.d.-b).

The ENERGY STAR® energy performance scale is applicable to MURBs of up to three floors (U.S. Environmental Protection Agency, n.d.-a). This leaves a gap in benchmarking the energy consumption of high-rise MURBs.

PM energy benchmarking calendarizes monthly readings prior to weather normalization (U.S. Environmental Protection Agency, 2011b). PM first adjusts energy data to fit calendar months. It calculates the mean daily energy consumption based on monthly readings and generates a new monthly reading based on calendar months. Then the model matches energy consumption to the weather data for the building location and adjust the readings to the equivalent for 30-year conditions. Finally PM calculates the correlation between energy and weather and computes the annual energy consumption (U.S. EPA, 2011).

The theoretical base of weather normalization in PM is equivalent to PRISM. An additional assumption is made in PM that daily consumption remains constant in each reading period. The error in this assumption is elevated during the changing of season. For example, from the reading October 15 to November 15, PM assumes that the energy consumption is the same on any day during the time period. If the heating season started during this period, then the energy consumption is different on October 15 and November 15. As a result, the October reading input into the weather normalization is higher than the actual use while the November is lowered. The U.S. EPA has not provided validations on this assumption.

2.7 Evaluation of True Effectiveness of Energy Conservation Measures

Engineering models are popular in the prediction of energy savings from retrofit programs. However, according to the U.S. National Research Council (1985), engineering models tend to overestimate energy savings. Many retrofit programs showed that the actual savings are far less than estimated, in some cases by as much as 50% (Metcalf & Hassett, 1999).

Engineering methods ignore some important factors, such as tenants' behavioural change, ongoing system maintenance, and other hidden inter-related effects. Those non-engineering factors may negatively impact the true effectiveness of the retrofit program. The discrepancy between estimation and actual savings may raise concerns from building owners/governments/utilities who want to make wise decisions on cost-effective upgrades. Reliable methods to estimate energy savings are integral to promoting energy conservation measures in the building sector.

The discrepancy between the estimated saving and the actual saving can be a result of rebound effects. The rebound effect refers to an increase in the demand for energy service after technological efficiency improvement (Greening et al., 2000). The rebound effect offsets the energy savings that were expected to be achieved (Sorrell et al., 2009). Technology improvement is the most important source of energy savings (Berkhout et al., 2000). From the economic perspective, the decreased energy demand may lead to price drop. The price drop would encourage the consumption of energy (Greening et al., 2000). If the use of space heating costs less, one may set the indoor temperature to a higher degree for a more comfortable living condition. When the cost of lighting drops, one may not bother to switching lights off when not in use. The behavioural changes are almost certainly negative on the benefits from energy conservation measures (Berkhout et al., 2000).

Chapter 3

3 Methodology

3.1 Overview

This research studied the energy consumption of 46 high-rise MURBs in Toronto. The energy benchmarking was developed to understand the current energy efficiency in the high-rise MURBs. The benchmarking was compiled by weather normalized annual energy consumption (NAC) of each MURB, which was calculated by PRISM. The GHG emissions benchmarking was developed accordingly.

To understand what factors influence overall energy consumption of the MURBs, the relation between NACs and building characteristics such as vintage, gross floor area, and occupancy were examined.

During the benchmarking process, the MURBs that had noticeable energy consumption changes were identified and the savings were quantified. The energy signatures of those MURBs were obtained from PRISM to discuss the energy demand changes.

The energy consumption was assessed using the simple ratio weather normalization (SRWN) method and EPA ENERGY STAR® Portfolio Manager (PM). The benchmarking and actual saving results obtained from different methods were compared with PRISM results.

The flow chart of the thesis is shown in Figure 3-1.

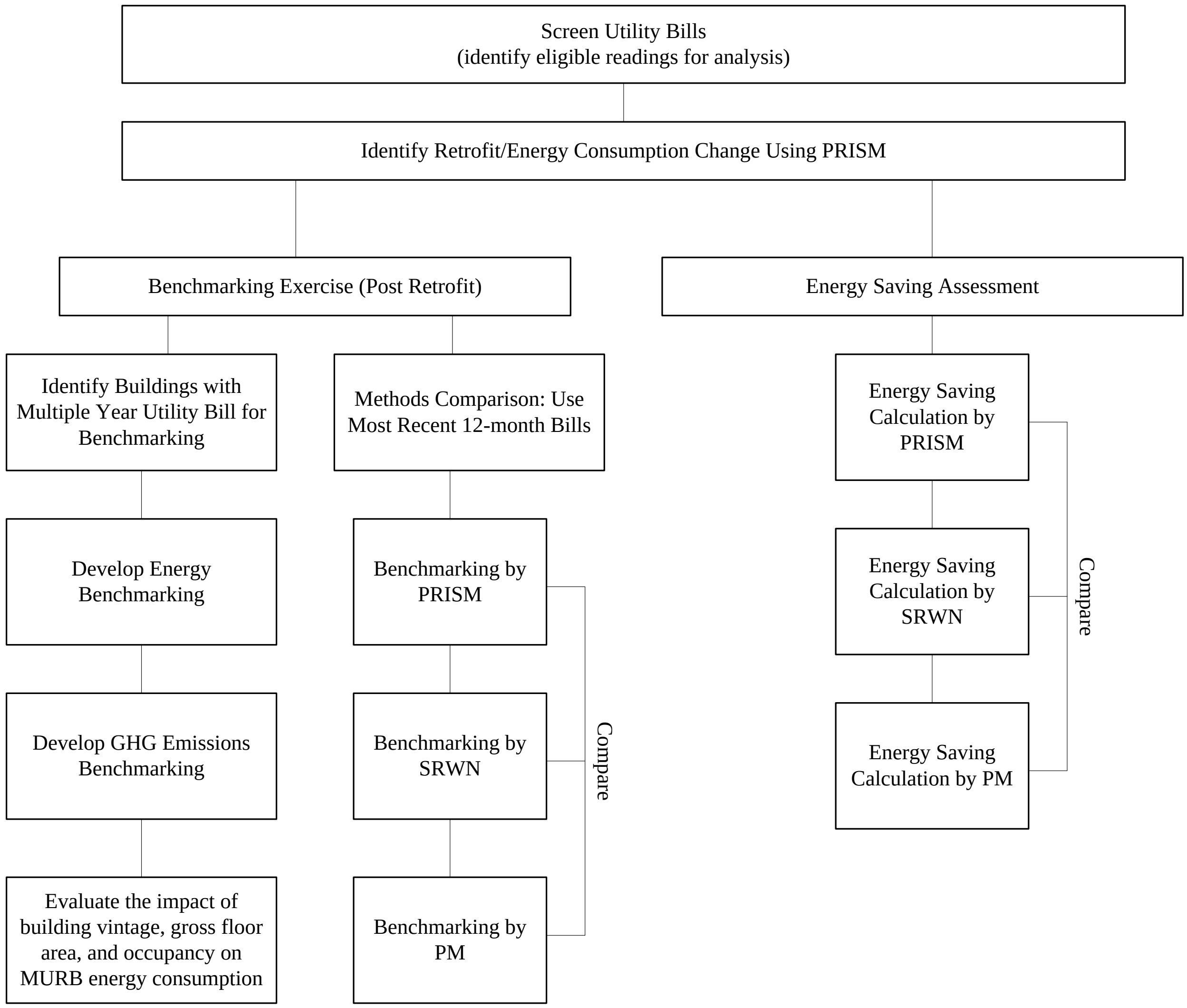

Figure 3-1: Overview of research methodology

3.2 Data Collection and Screenings

According to the agreement with the Tower Renewal Project, the City of Toronto Tower Renewal office was responsible for collecting data from building owners and providing it to this research project. The researchers from the university were not permitted to be in contact with building owners directly. As a result, it is vital to ensure the received data includes required information and feedback to the Tower Renewal office in case of missing or questionable information.

Due to the confidentiality issue, building location and utility bills are recorded in separate MS Excel files. Each building was assigned an ID, which was used through the research.

3.2.1 Requirements for Building Specification

This research proposed to investigate the relationship between MURBs' energy consumption and their building characteristics. A comprehensive survey was developed to gather the information to cover occupancy, building physical information, HVAC system, lighting systems, amenities, appliances, and retrofits during the provided billing period. An overview of this survey is shown in Appendix A. However, this detailed survey was not adopted by the Tower Renewal office. The office suggested that building owners may not be willing to provide detailed information and decide not to participate in the project. Instead, the author was passively waiting for data that the building owners are willing to provide. The author would highly recommend using the developed survey for data collection in the future.

3.2.2 Requirements for Utility Bills

The minimum requirement for PRISM analysis is six bimonthly meter readings or 9 monthly readings in one year (Fels et al., 1995). The missing monthly data cannot be consecutive. Data should be carefully screened to ensure each meter reading contains reading date and corresponding consumption.

The missing months affect PRISM determining the number of days for the billing cycle; thus, it is very important to identify the missing month's utility bills. The missing readings are recorded as "-1" in PRISM (Fels et al., 1995). Goelzt and Hirst (1987) argued that for the heating dominated climate, missing winter readings would underestimate the NAC, while missing reading in fall/spring would not affect the reliability of the NAC. The NACs must be based on utility readings that represent the energy consumption in all four seasons, especially the winter.

PRISM calculates the NACs using linear regression models. A reliable NAC must meet two requirements in the linear regression models: R^2 above 0.7 and CV below 7% (Fels, 1995). The R^2 indicates the goodness of the fit between the dependant variable, the NAC, and the independent variable, HDD/CDD. The R^2 is between 0 and 1, and a good model has a value close to 1.0. The CV is a measure of dispersion of a probability distribution. A good PRISM model has a CV closes to zero (Fels, 1995).

The actual utility data may contain problematic readings, such as missing readings, multiple-monthly readings, unreliable reading dates, missing digits, duplicate readings etc. The problematic readings may lead to discrepant NACs results even under robust mode. When problematic readings were identified, each situation was scrutinized to ensure R^2 is above 0.7 and CV is below 7%. If R^2 and CV do not meet those requirements, the energy consumption of the MURB is poorly linearly related to the outdoor temperature; thus, the weather normalization would be inappropriate. Those questionable readings should be deleted in the PRISM analysis.

3.2.3 Weather Data

Historical daily mean temperature is retrieved from Environment Canada National Climate Data and Information Archive. The weather monitoring station located at Toronto Lester B. Pearson International Airport. The location is 43°40'38.000" N latitude and 173.40 meter elevation. The WMO ID is 71624 (Climate Data and Information Archive, 2012).

Weather normalization period is from January 1, 1981 to December 31, 2010. The annual HDDs and CDDs based on 18°C from 1981 are displayed in Figure 3-2. The coldest year for the

30 year was 1989, with an HDD of 4246. The hottest year for the time period was year 2005, with a CDD of 536. The 30 years average HDD and CDD based on 18°C are 3870 and 305 respectively. This average weather information is called long-term weather, which was used to represent a typical year of Toronto weather for the chosen 30 years. The weather data must cover the utility reading dates; thus, were updated monthly during the research.

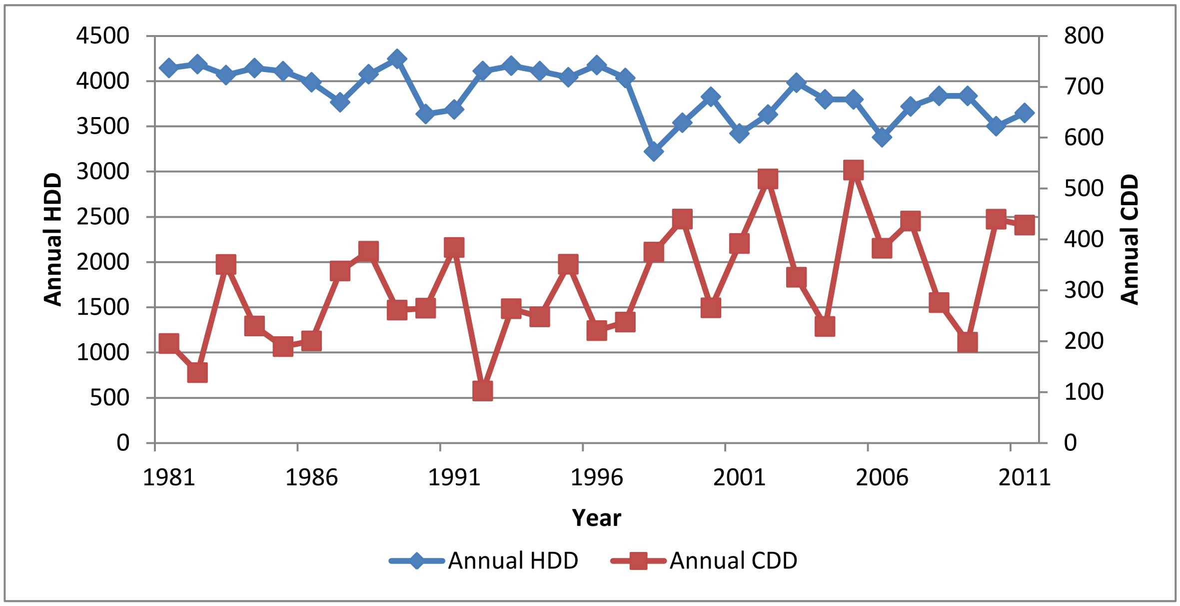

Figure 3-2: Toronto annual HDD and CDD 1981-2011 (data source: National Climate Data and Information Archive)

3.3 PRISM Analysis

PRISM was developed by the Center for Energy and Environmental Studies of Princeton University, with co-funding from participants in the Advanced PRISM Project (Fels, 1995). The most recent release was in January 1995, the PRISM® (Advanced Version 1.0), which was used in this research (Fels, 1995).

3.3.1 Compatibility of PRISM

The author tested PRISM on different computer systems. PRISM is compatible with Windows XP and Windows 7 32- bit system. For Windows 7 64-bit system users, the virtual PC, Windows XP mode should be installed.

The data can be input into PRISM either by importing text file, or by manual input. As the data were recorded in MS Excel format, they must be saved as text (delimited) format in order to input to PRISM.

3.3.2 TPS File Generation

Temperature file is saved as TPS format by PRISM. Daily temperatures must be converted from degree Celsius to Fahrenheit. If using Celsius degree as input unit, PRISM treats the temperature file as an error, because the default temperature range is on the Fahrenheit scale. Temperatures must be zero decimal digits. Using one or more decimal digits will cause "input past end of file" error.

The daily temperature is recorded in the format shown in Table 3-1. Temperature is imported to PRISM using "column to TPS" function as shown in Figure 3-3 and 3-4.

Table 3-1 Weather Data Format for PRISM

Month	Day	Year	Mean Temperature (°F)

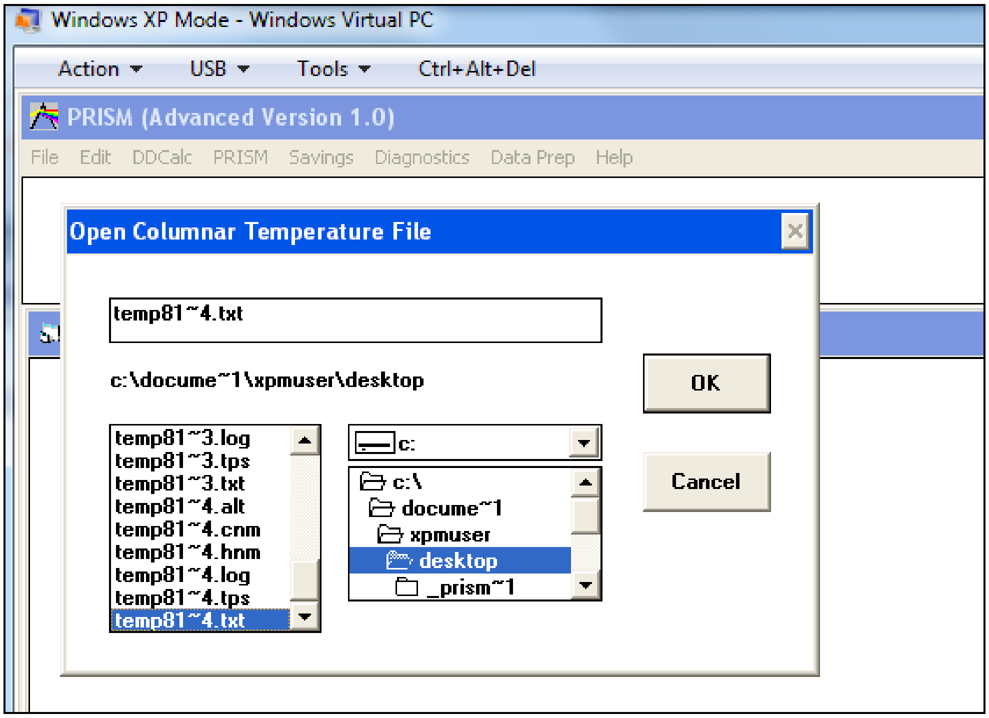

Figure 3-3: Screen grab of importing text file to PRISM using "column to TPS" function

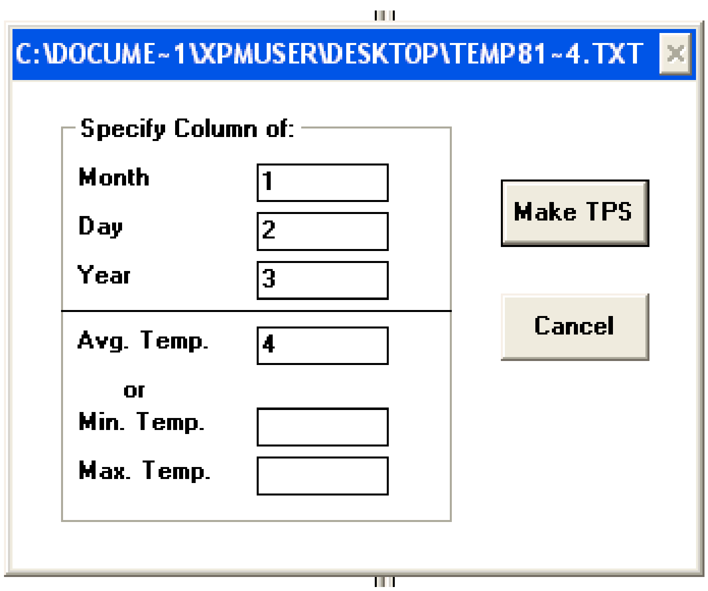

Figure 3-4: Screen grab of importing text file to PRISM using "column to TPS" function

To calculate the HDDs and CDDs for the chosen 30-year period, the starting date January 1, 1981 and the ending date December 31, 2010 were input into the options in the format of

MM/DD/YY. The lowest and highest temperature must be within the lower and upper bound. PRISM requires the temperature within the range of - 50°F (-45.6°C) and 120°F (48.9°C). The HDDs and CDDs calculation setting is shown in Figure 3-5.

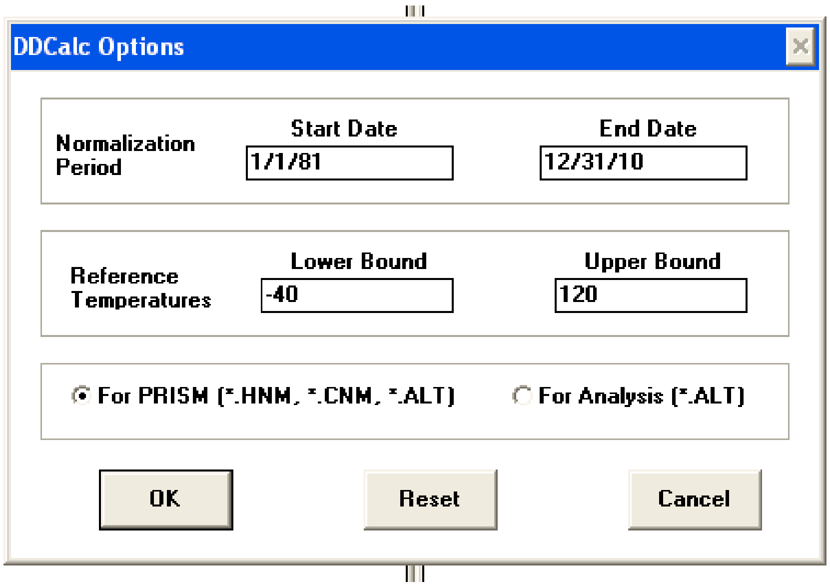

Figure 3-5: Screen grab of HDDs and CDDs calculation setting for PRISM

After calculating the HDDs and CDDs in PRISM, three files were created with suffix .cnm, .hnm and .alt. The graph for degree-day per day based on different reference temperature was created as shown in Figure 3-6. The newly created file and the previous TPS file are the complete temperature data file for PRISM energy consumption analysis.

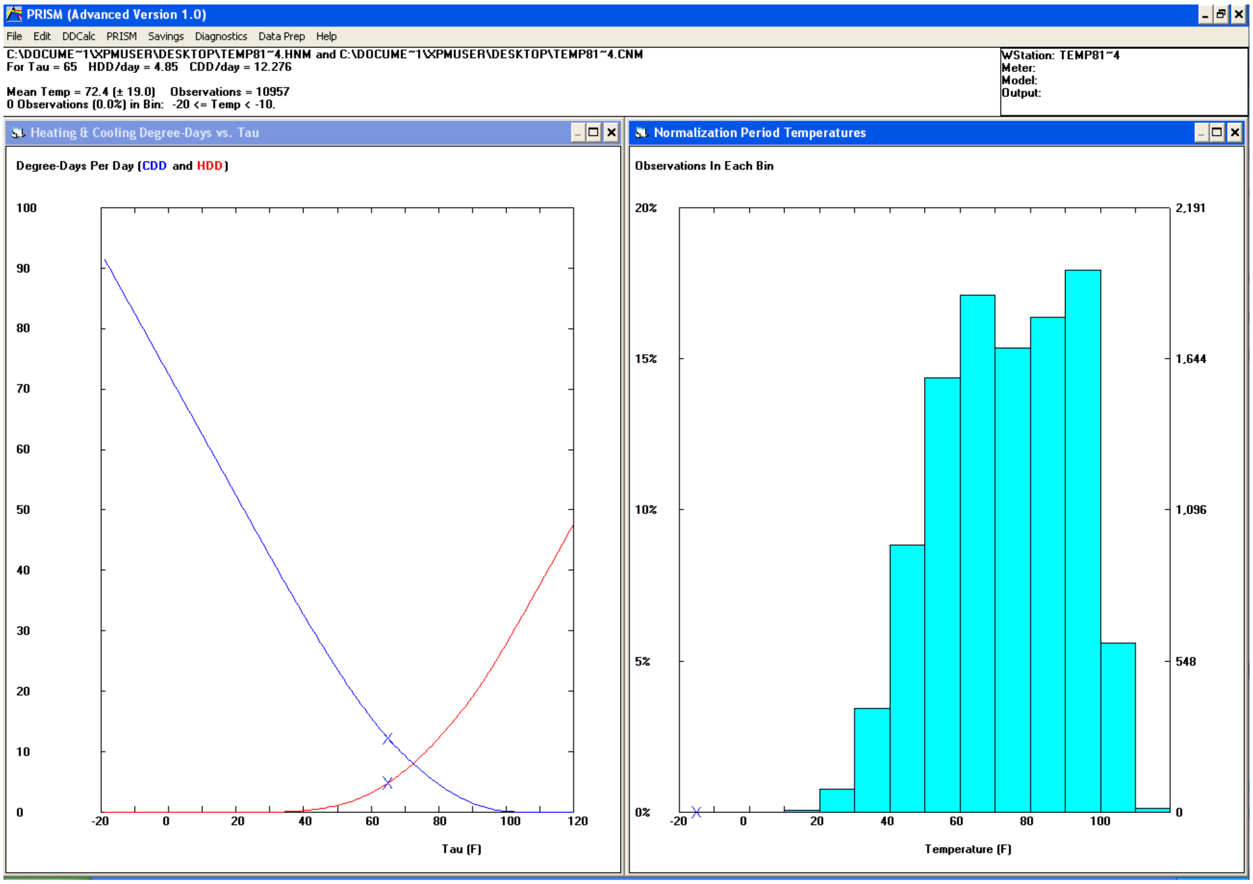

Figure 3-6: Screen grab of PRISM output for degree-day per day based on different reference temperature

3.3.3 Meter File Generation

PRISM uses meter file to store billing information. To be compatible with PRISM meter input format, the utility billing records were re-formatted to Table 3-2. The billing information was input into PRISM using "column to MTR" function. The setting is shown in Figure 3-7. The input column numbers in Figure 3-7 corresponds to columns in Table 3-2. After the billing record input into PRISM, the meter file was created with the MTR suffix.

Table 3-2 Utility billing input format for PRISM

Building ID	Reading Month	Reading Date	Reading Year	Energy Consumption	Energy Unit	PRE/POST Label	Group Label	Estimate/Actual Reading

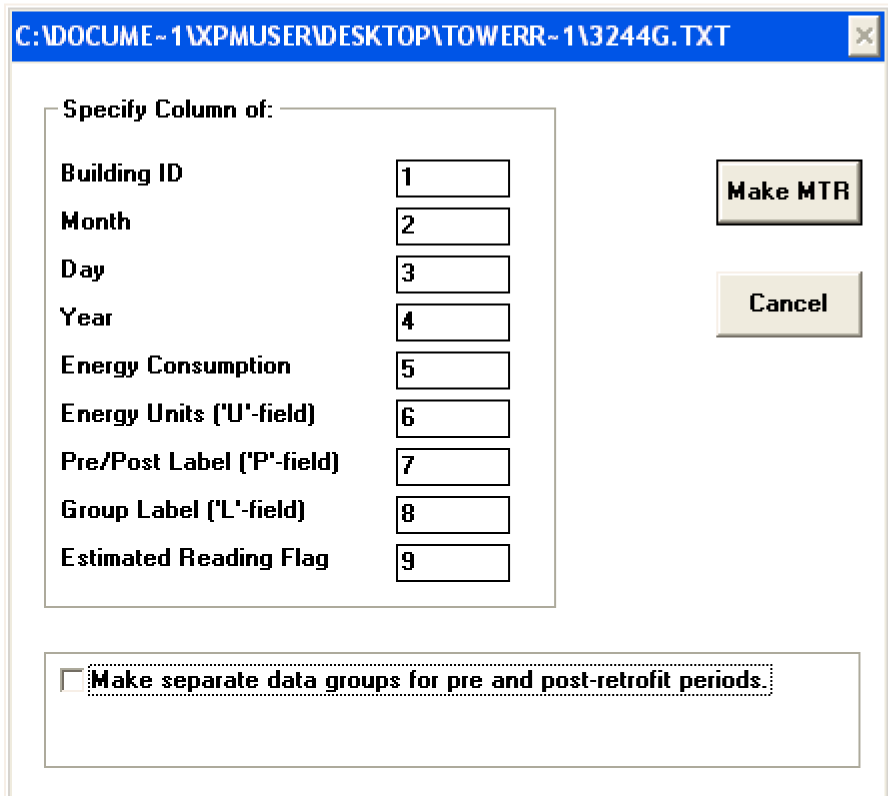

Figure 3-7: Screen grab of input billing information to PRISM using "column to MTR" function

The building ID must begin with a letter, either capital or lower case. The building ID which begins with a numeric number the meter will lead to the "Illegal function call" error.

3.3.4 NAC Calculation

3.3.4.1 PRISM Model Selection

PRISM has three basic models to calculate NACs: heating only (HO), cooling only (CO), and heating-and-cooling (HC). The current version of PRISM incorporates "robust" function to the analysis. Under the robust mode, PRISM assigns lower weights to the outliers than normal readings, and uses adjusted values for regression analysis. This is to make the best use of the data including the outliers.

PRISM can compare HO, HO robust (HO-R), and HC modes on the same chart, using "compare models" function under "Diagnostics" tab. An example of using "compare models" function is given in Figure 3-8, which shows the PRISM output plots for building "3898" electricity consumption. The R^2 for HO, HO-R, and HC are 0.052, 0.178 and 0.833, and CV values are 0.8%, 0.6% and 0.4% respectively. The HC mode is the only model that meets the reliability requirements, which has an $R^2 > 0.7$ and CV < 7%. The result indicates a good correlation between energy consumption and HDD/CDD. Therefore, building 3898 requires both cooling and heating related electricity consumption. The HC mode was chosen to analyze the NAC of building "3898" electricity consumption.

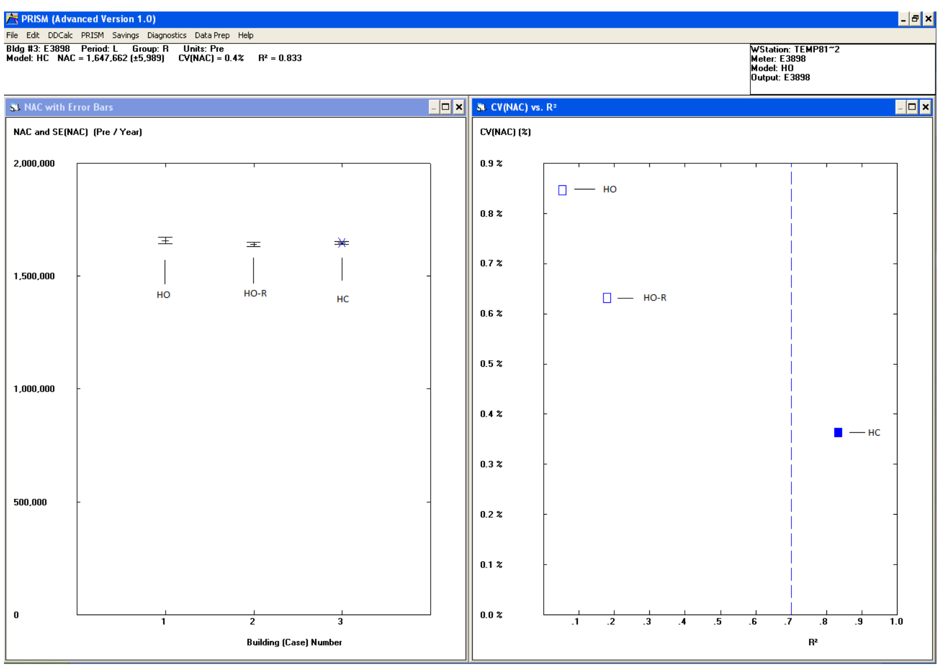

Figure 3-8: Screen grab of PRISM result using "compare mode" function for building "3898" electricity consumption. The unit for NAC is kWh/year

The selection of model type can also be confirmed by screening energy use per day plot with energy use by number of HDD/day plots, which is given by PRISM. Figure 3-9 shows the daily electricity consumption of each reading cycle of building "3898". The peaks in the energy use per day in winters and summers indicate the increased energy demand in summers and winters. This further observation confirmed that HC mode should be chosen for benchmarking.

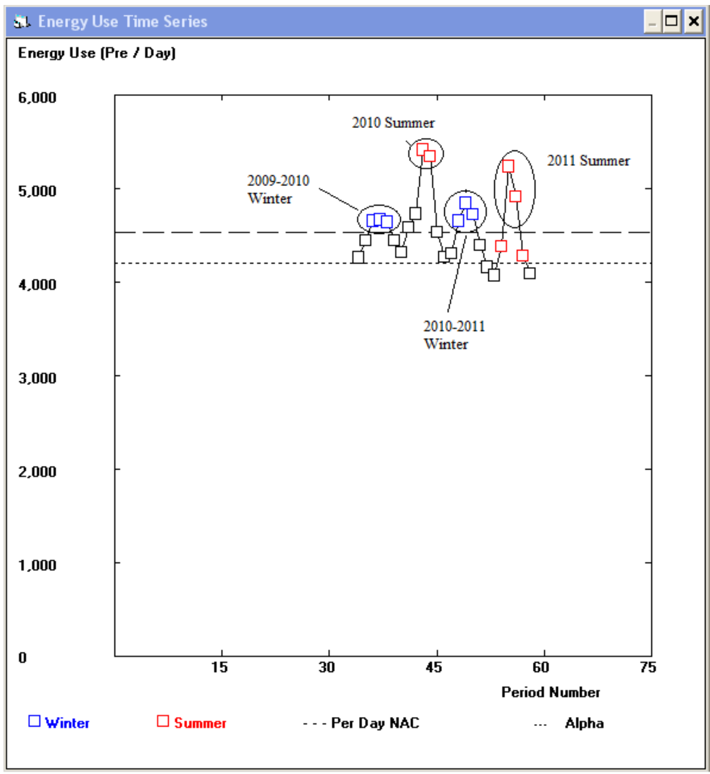

Figure 3-9: Screen grab of energy use time series and energy use vs. degree days of a typical electric heating and cooling building, building "3898" electricity consumption. The unit for energy use is kWh/day

An example of PRISM output for heating-only buildings is given in Figure 3-10. Daily energy consumption peaks are identified in winter only. The rest of the months represent the base-load consumption.

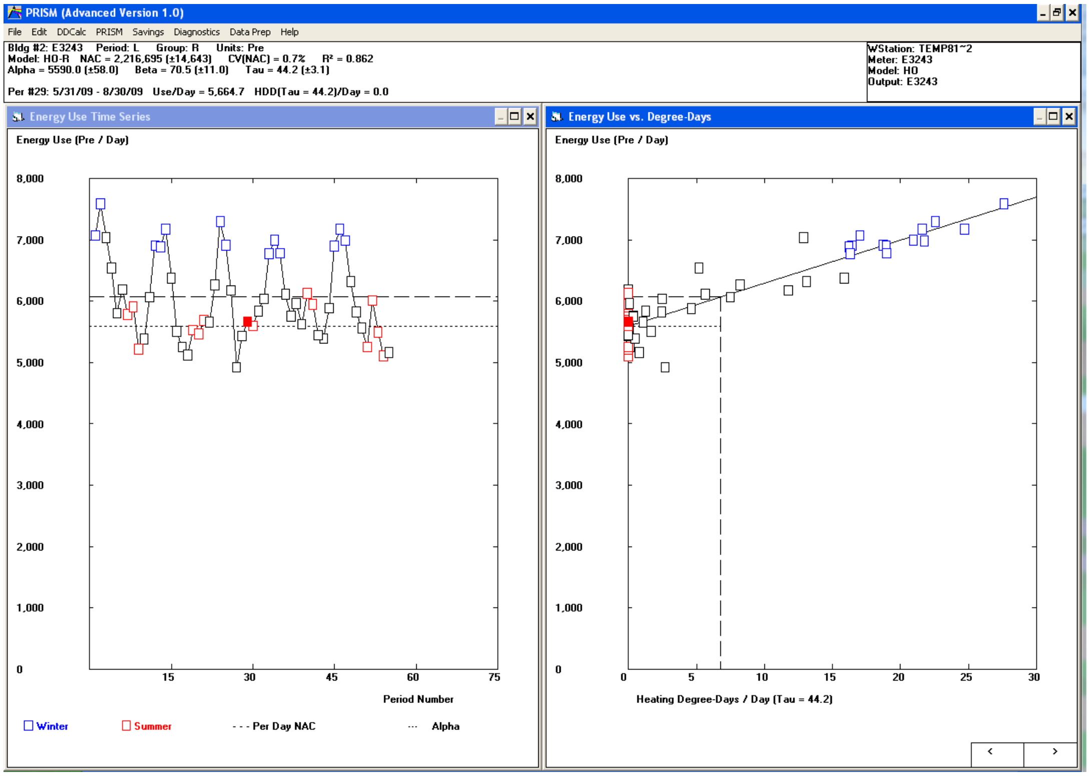

Figure 3-10: Screen grab of energy use time series and energy use vs. degree days of a typical electric heating only building, building "3242". The unit for energy use is kWh/day

3.4 Retrofit Identification and Quantification

Received data contains multiple years' bills without the information on the retrofit. Some of the buildings have drastic energy consumption changes in the billing period. Building "4079" is an example of such buildings (Figure 3-11). The daily gas consumption in the recent two winters dropped from approximately 4000 m^3 to below 3000 m^3 per day. To identify if the NAC of the last two years decreased, the NAC were calculated on a yearly basis. The results are given in Table 3-3.

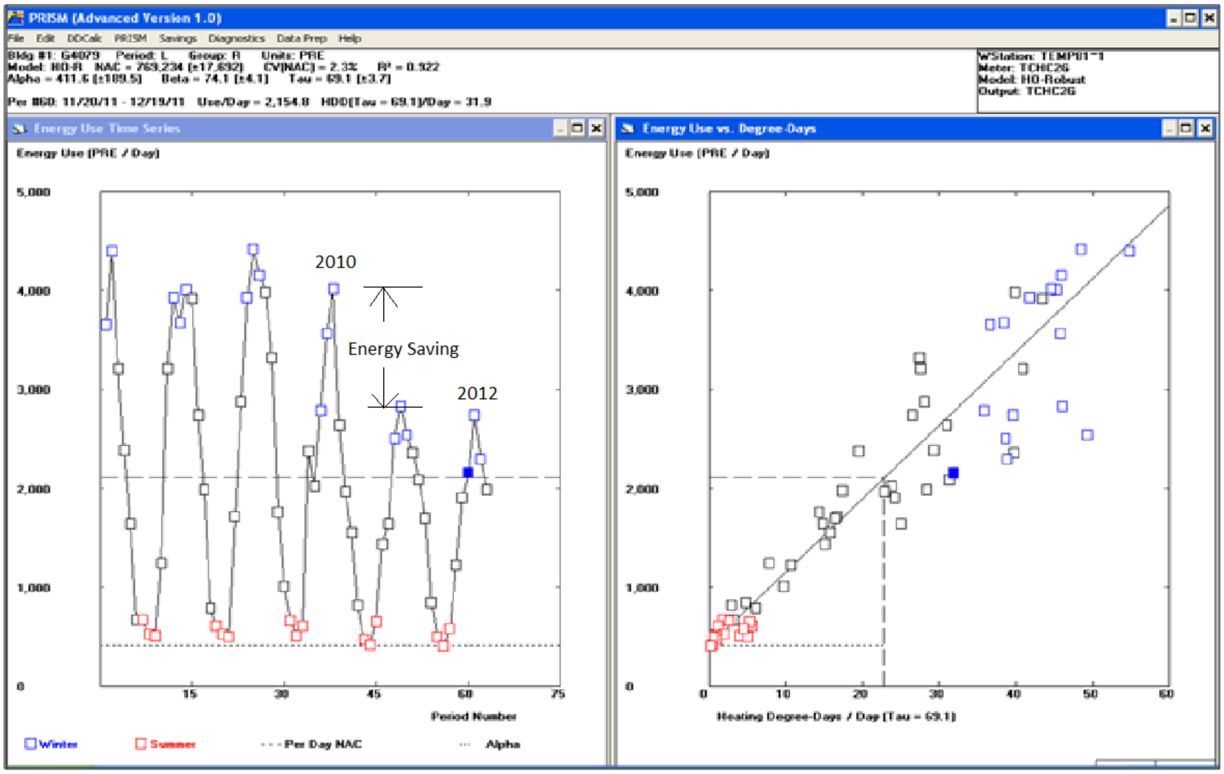

Figure 3-11: Screen grab of energy use time series and energy use vs. degree days of a retrofitted building (building "4079") gas consumption. The unit for energy use is m^3/day

Table 3-3 Building 4079 gas NAC based on bills from different years

Normalization Time Period	R^2	CV (%)	NAC (m^3)	NAC Compared with Previous Year
March 1, 2011 - February 29, 2012	0.975	3.0	629920	3%
March 1, 2010 - February 28, 2011	0.968	3.0	609306	-22%
March 1, 2009 - February 28, 2010	0.935	5.3	782901	-8%
March 1, 2008 - February 28, 2009	0.992	1.9	848718	1%
March 1, 2007 - February 29, 2008	0.987	2.3	844452	-

There are two possible retrofit in building "4079". The major NAC change occurred in the year 2010-2011. The gas NAC dropped 22% comparing with the previous year. It is likely that a retrofit was implemented during the non-heating season in 2010. Since the exact retrofit time during the non-heating season was unknown, and there were more than 1-year utility readings in the data, the uncertain months were not counted as neither before nor after the retrofit. In this case, the energy saving is calculated as the difference the NAC of March 1, 2009 to February 28, 2010, and after November 1, 2010. A minor decrease of 8% occurred in year 2010. In order to calculate the NAC, 12 monthly readings that centered at the 2010 winter were used. Since the NAC difference between the first two years was 1%, it could be inferred that no retrofit was implemented during that time. Therefore, the March 2007 – March 2009 period was treated as the pre-retrofit stage. The calculated NAC of each time period is displayed in Table 3-4. The gas savings were 7% and 21% for the two retrofits, with an overall of 36% saving.

Table 3-4 Building 4079 gas saving assessment

Observed Energy Consumption Period	NAC (m^3)	R^2	CV	Energy Saving (Comparing with Previous Year)
March 1, 2007 - February 28, 2009	842871	0.989	1.5	
March 1, 2009 - February 28, 2010	782901	0.935	5.3	7%
November 1, 2010 - February 29, 2012	618338	0.976	2.2	21%
Overall Saving				36%

In general, the monthly reading at the change point should not be included in the analysis. This monthly reading contains the energy consumption pattern of both before and after retrofit; thus it does not solely reflect either energy consumption pattern. In some MURBs, it may take a few months for the energy consumption to stabilize. A possible explanation is that the implementation of retrofit in those MURBs takes time. This situation is reflected by fluctuations in the monthly readings, and usually low R^2 and/or high CV. The post retrofit NAC calculation should be always based on stabilized energy consumption pattern. Therefore, when low R^2 and/or high CV values occur in the post retrofit analysis, the first few months in the post retrofit period should be considered as stabilization period, and excluded from post retrofit NAC analysis.

In this research, when the NAC difference of two adjacent years is above 5%, it is assumed retrofit was implemented. The NAC difference within 3-5% range is considered as unknown fluctuations. In both scenarios, requests for retrofit information were sent to the Tower Renewal Office.

Retrofits change the energy signature of the building. The reference temperature, heating slope, cooling slope, and base load before and after the retrofit were compared. The energy signature is an indication of the changes in energy demand in the building.

3.5 Benchmarking Establishment

Energy benchmarking was compiled of NACs from post retrofit time period. The overall NAC is the sum of electricity NAC and gas NAC. The overall NACs were ranked from lowest to the highest as the benchmarking. Seven energy performance indicators (EPIs) were developed by normalizing PRISM analyzed results to the gross area of the building. The EPIs are: 1) total energy consumption, 2) total electricity consumption, 3) base electricity consumption, 4) cooling-related electricity consumption, 5) heating-related electricity consumption, 6) base gas consumption, and 7) gas heating consumption. EPIs use kWh/m^2 as the standard unit. One cubic meter natural gas is converted to 10.42 equivalent kWh (Natural Resources Canada, 2009).

3.6 Results comparison

Two commonly used weather normalization methods, SRWN and PM, were selected to compare with PRISM. The features of each method are summarized in Table 3-5.

The PM is very strict with the meter readings. The benchmarking must be based on 12 consecutive monthly readings. To be consistent with the input data, the benchmarking for comparison analysis uses 1-year recent monthly readings.

Table 3-5 Features of PRISM, SRWN and PM

Weather Normalization Methods Comparison			
	PRISM (Fels, 1986)	**SRWN (ASHRAE, 1985)**	**PM(U.S. Environmental Protection Agency, 2011a)**
Optimized Reference Temperature	√	x	√
Missing Meter Reading Allowed	√	√	x
Detect Outlier Meter Reading	√	x	√
Reliability Test	√	x	√
Identify Energy Consumption Change	√ (By observation)	x	x
Optimizing the Outliers	√ (Assign lower weight)	x	x (Delete the outlier)
Monthly Reading Date During Analysis	Actual (on bill)	Actual (on Bill)	Prorated to 1st of each month

3.6.1 SRWN Benchmarking

SRWN method requires 1-year energy consumption data and corresponding weather information. Since energy consumption and weather data are on an aggregated level, the readings in the year can be either monthly or multi-monthly. The flexibility of data input is an advantage of SRWN. For some buildings, there is only 1 reading for the full summer season. Using this aggregated readings do not affect the calculation of NAC. The SRWN method cannot detect the outlier in the data; the data screening process is essential.

The actual annual HDD, the HDD_a, is the sum of daily HDD from the starting date to the ending date of the bills. In the received data, different buildings have different utility readings dates. In order to simplify the HDD_a calculation process, a C++ program was written as shown in Appendix B. When a reading is missing, the corresponding HDD must be excluded from the HDDa, to ensure that the HDD_a is calculated according to the available dates.

In this research, the typical weather from January 1, 1981 to December 31, 2010 is used as the long-term annual HDD, the HDD_L. The HDD_L is 3870 based on 18˚C.

3.6.2 PM Benchmarking

PM benchmarking tool is a web-based application. The minimum required input data are the location of the building, building gross area and 1-year utility bill. If the monthly readings are not on the first day of the calendar month, at least 13 monthly readings are needed, because PMs adjusts monthly readings to calendar months before weather normalization (U.S. Environmental Protection Agency, 2011a). The two consecutive readings have to be read within 60 days (U.S. Environmental Protection Agency, 2011a). All The readings dates have to be continuous. Benchmarking will not be provided if one or more readings are missing.

PM generates benchmarking report on weather normalized annual electricity consumption, gas consumption, and overall end-use consumption (U.S. Environmental Protection Agency, 2011a). Those three outputs were used for this research. PM also provides the primary energy consumption. However, the indexes that are used to estimate primary energy consumption are based on U.S. statistics (ASHRAE, 1985; U.S. Environmental Protection Agency, 2011a). Those estimates are inappropriate for Canadian MURBs.

For building types other than MURBs, an ENERGY STAR rating for the building is provided. The rating is generated by comparing the studied building with similar buildings from a national survey conducted by the Department of Energy's Energy Information Administration

(U.S. Environmental Protection Agency, n.d.-b). Due to lack of data on MURBs, this rating is not available for buildings of this category.

3.6.3 Retrofit Comparison

The retrofit time period that estimated by PRISM was used for SRWN and PM energy saving assessment. Although the retrofit analysis stated in Section 3.4 uses multiple year utility bills, in this section, all pre-retrofit and post-retrofit weather normalization analyses were all based on 1-year utility bill. This was to ensure that the benchmarking results from three methods were based on same data. The energy savings were quantified as the difference between the post-NACs and the pre-NACs.

Chapter 4

4 Results and Discussion

4.1 Data Collection

In order to investigate what factors influence the energy consumption of high-rise MURBs, the original proposal discussed with the project partner, the Tower Renewal Office, was to collect data that included building physical specification, occupancy and utility consumption. Ideally, the data would include the building floor plan, information on HVAC systems and building envelope, and any changes that were applied in the recent past. The purpose of establishing the database is not only to provide benchmarking but also to develop an artificial neural network (ANN) model to examine the relationships between various factors.

The feedback from building management showed little interest in cooperating with an intensive study. The building owners were willing to provide the minimum required data for benchmarking purposes. One of the possible reasons is the limited resources allocated to energy management. Building management had also shown concerns for the complexity in collecting detailed information from each building because many data were held by different functional groups within the company. Collecting all of the information for an ideal study requires communication with the property management, which is unlikely to be achieved within a short-time period. The Tower Renewal Office suggested that the comprehensive questionnaire might discourage the building owners from participating in the project, especially at the initial stage.

Thus, the data collection was comprised of:

- Building characteristics: gross floor area, number of floors, number of units, and year of construction;

- Occupancy information: percentage of occupied units by month;
- Utility bills: monthly electricity and gas bills for 3-5 years.

During the analysis of data, energy consumption pattern changes were identified in the majority of the buildings. Requests for information on building retrofit and other activities that may cause these changes were sent to the Tower Renewal Office. However, this further information was only provided for one MURB. As a result, all energy saving assessments carried out in this research are based on utility bills. The reason for the energy consumption changes will not be discussed in this thesis.

The established energy benchmarking and individual building performance was reported to the Toronto Tower Renewal program. A sample report for building “4079” is given in Appendix C.

4.2 Survey result overview

The Tower Renewal office provided data for 46 MURBs participating in the project. Utility bills covering a time span of 2-5 years varied by buildings. As the project progresses, the number of the MURBs will increase. In the current database, 45 buildings are gas heated. Only building “3902” is solely heated by electricity. Electric heated buildings are usually more efficient than gas heated buildings; thus, building “3902” is only used as a reference in this project and will not be used for further analysis and comparison.

The number of floors ranged from 7 to 24, as shown in Figure 4-1. The mean number of floors is 16 with a standard deviation of 4.

The gross floor area of MURBs in this study ranges from 9240 m^2 to 34,850 m^2. The mean gross floor area is 21317 m^2 with standard deviation of 5635 m^2. The number of residential units is between 128 and 439, with a mean of 252 units. The mean floor area per unit (including common area) is between 55 m^2 and 127 m^2.

Previous research showed that occupancy type has great influence on the energy use (Enermodal Engineering Limited, 2001). Although occupancy type was not specified in the data, the average unit size to some degree reflects possible occupancy type.

The mean floor area per unit is shown in Figure 4-2. Unit size in buildings “5528”, “5521”, “5634”, “3497”, and “4790” units are less than 60 m^2. Units in those MURBs are likely to be occupied by single persons or small families. Building “Bldg5”, “Bldg1” and “Bldg2” have a mean of more than 120 m^2 per unit, possibly with many larger units to accommodate larger families.

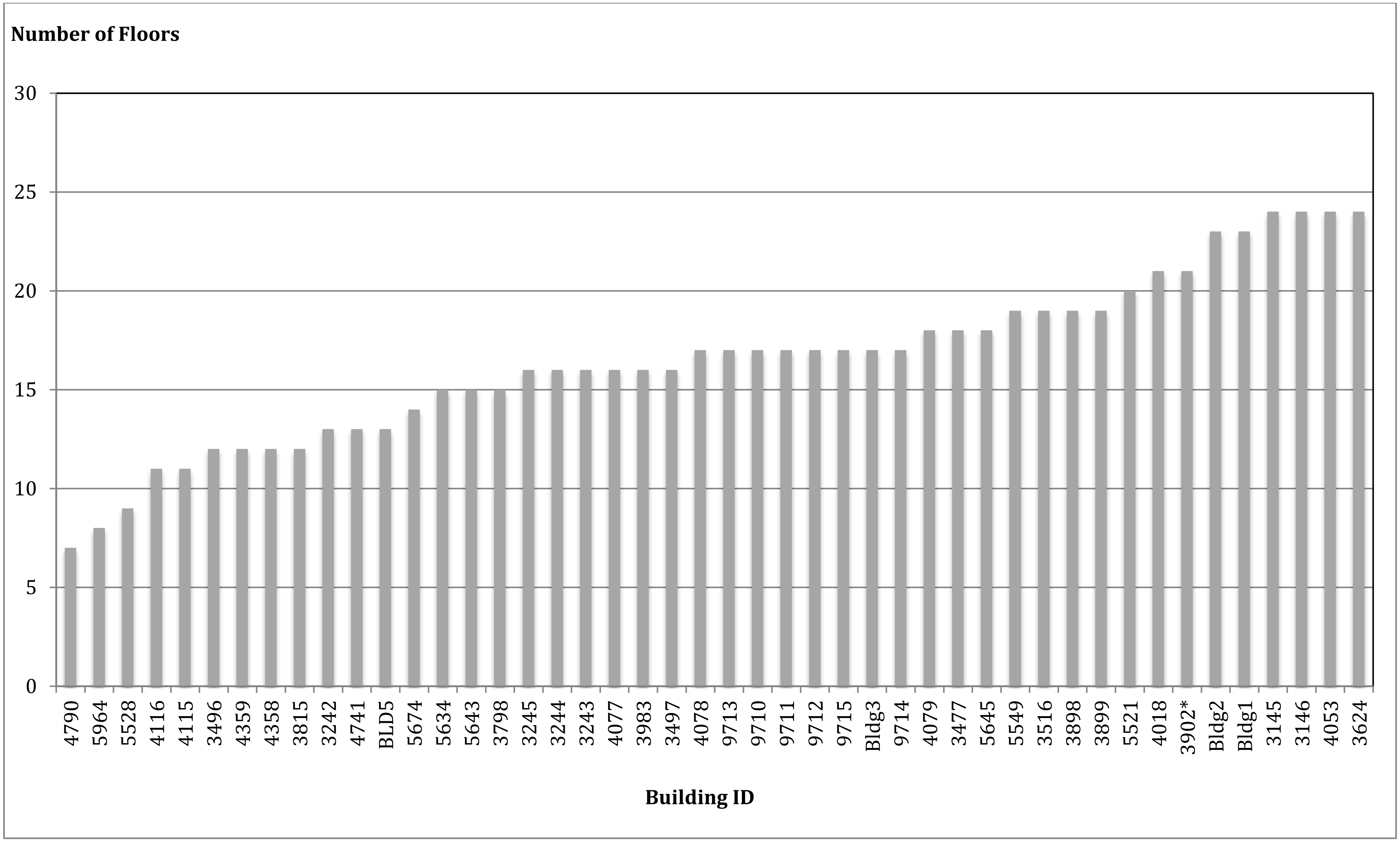

Figure 4-1: Number of floors of the 46 GTA high-rise MURBs studied, *building 3902 is the only electric heated building

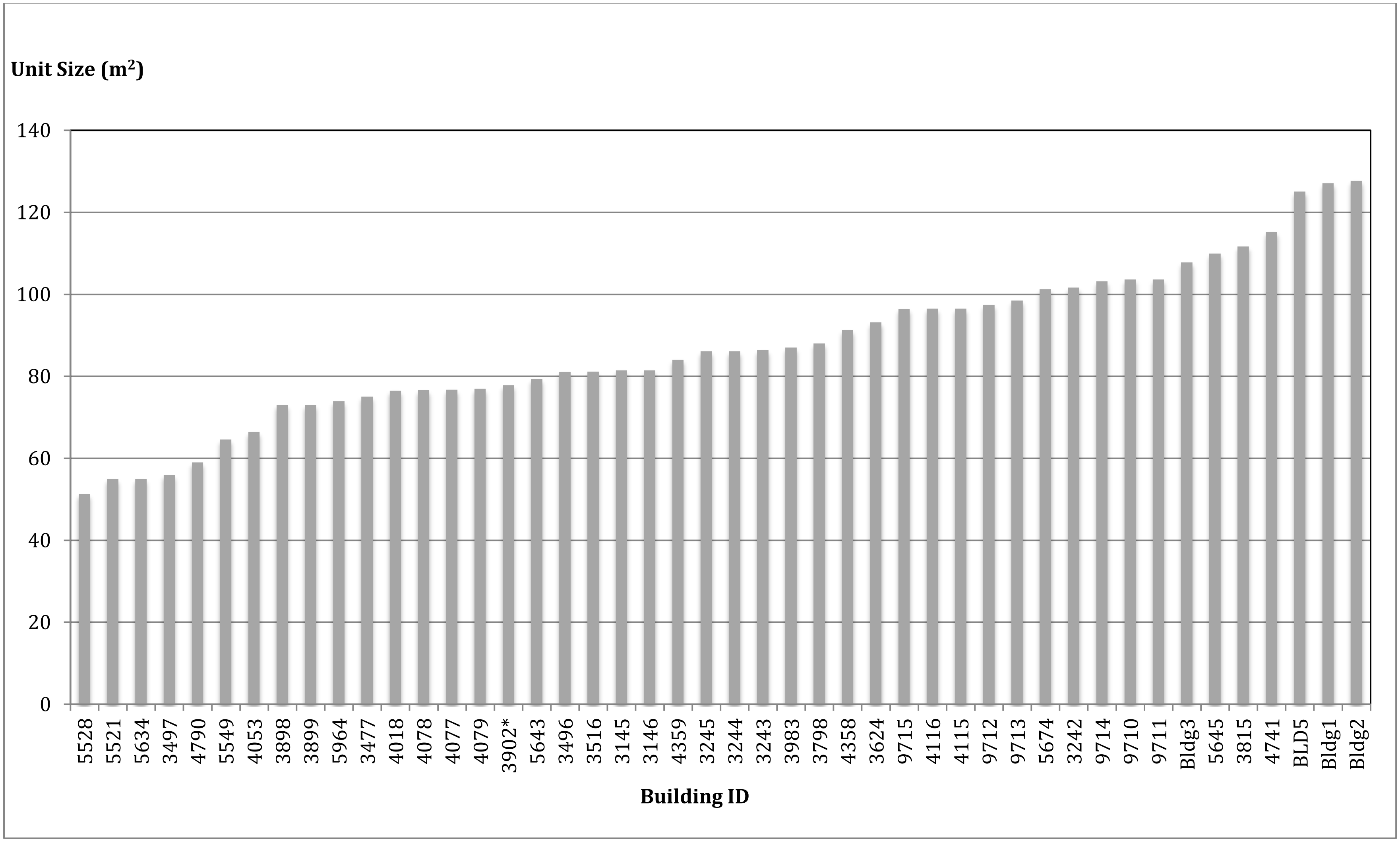

Figure 4-2: Average size of units (m^2), *building "3902" is the only electric heated building

4.3 Benchmarking Result using PRISM

Utility bills were inputted into PRISM with temperature filed from January 1, 1981 to April 30, 2011. Each MURB was investigated individually to identify the most recent energy consumption trend. The benchmarking presented in the following section used the maximum number of historical data that after possible retrofit.

The PRISM analysis in this research shows that the energy consumption is linearly related to outdoor temperature. The R^2 in the linear regressions for all buildings are between 0.70 and 0.99 range. The mean value for standard deviation is 0.85 for electricity and 0.96 for gas consumption. This indicates that the assumption on the linear relation between energy consumption and weather is statistically reliable, especially for gas consumption, which is mainly used for heating.

4.3.1 Benchmarking Result by PRISM

The energy benchmarking by PRISM is normalized to the 30-year typical weather of Toronto, from January 1, 1981 to December 31, 2010. The weather information is obtained from National Climate Data and Information Archive. The weather is monitored at Toronto Pearson International Airport. The mean annual HDD and CDD based on 18˚C are 3870 and 305. The distribution of normalized annual energy consumption is shown in Figure 4-3. The median of NAC is 334 kWh/m^2. In the 45 gas-heated building, 82.5% of which have an EPI ±15% of the median, which is 284-384 kWh/m^2.

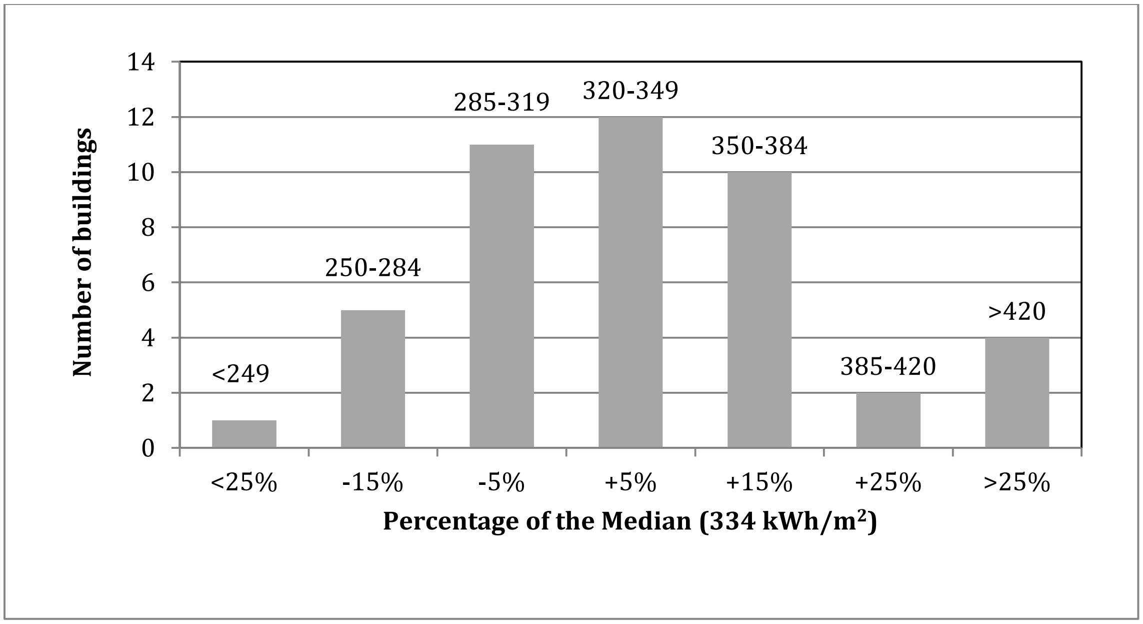

Figure 4-3: distribution of energy efficiency of 45 gas-heated MURBs

The energy benchmark with the estimated end-uses for 46 high-rise MURBs in the GTA is presented in Figure 4-4. For total energy consumption, building 3902, the electric-heated building showed much higher energy efficiency than other gas-heated buildings. The normalized annual energy consumption for the electric-heated building is 174 kWh/m^2. For the 45 gas-heated high-rise MURBs, the range of NAC is 242 – 453 kWh/m^2, with a mean of 336 kWh/m^2 and standard deviation of 51 kWh/m^2. The coefficient of variation, CV, of the sample is 15.1%. The benchmarks used in Figure 4-4 are shown in Appendix D.

The statistics for benchmarking results are given in Table 4-1. The result shows that the variations of overall energy consumption come mainly from gas consumption. The variation for electricity is relatively small. The CV for total electricity consumption and base electricity consumption are 14.2% and 12.7% respectively. This shows that the electricity consumption is comparable among these MURBs. On the other hand, heating-related electricity and cooling-related electricity showed large variations with CV 49.9% and 82.5%. This part of energy use is more likely to be caused by different and unpredictable behaviour of tenants in each MURB. The highest electric heating demand, 20.1 kWh/m^2, is identified in building “5964”. This building is also the most energy efficient building on total gas consumption and overall energy consumption. The gas heating for building “5964” is 85 kWh/m^2, only half of the average. The gas heating is used for central space heating. The high electric heating demand can be explained by the insufficient heating provided by the central space heating, and so tenants used other devices to improve comfort. Even so, the energy consumption for space heating purposes is combined gas and electricity consumption, at 105 kWh/m^2; still much lower than the mean heating consumption.

Building “5964” is a relatively efficient MURB, and meanwhile possibly provided space heating to tenants at minimum level. This MURB also shows the highest cooling demand, 19.2 kWh/m^2. The other MURB that had a high demand for cooling is building “5528” at 13.5 kWh/m^2. All other MURBs consumed less than 8 kWh/m^2 energy for cooling. One common factor in these two MURBs is that both MURBs have small units. The mean floor area per unit of building “5964” and building “5528” are 74 m^2 and 51 m^2 respectively. However, other MURBs of similar unit size do not show this trend.

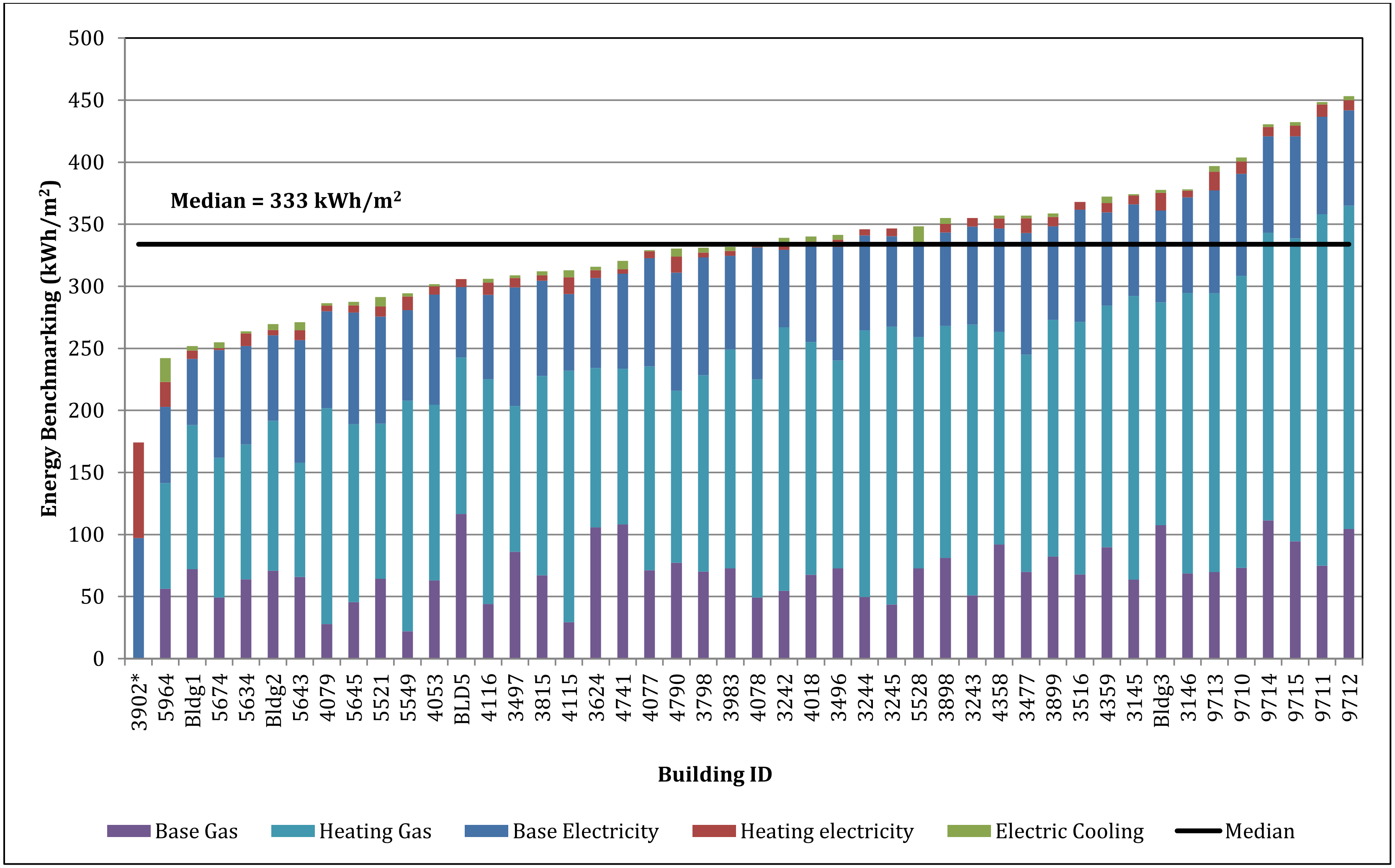

Figure 4-4: Energy benchmarks of 46 GTA high-rise MURBs. *Building "3902" is a electric heated building.

Table 4-1: Summary of energy benchmarks of 45 gas-heated high-rise MURBs in GTA

		Total Energy Consumption (kWh/m²)			
Normalized Annual Consumption - Overall	Lowest Consumption	242			
	Highest Consumption	453			
	Mean	336			
	Standard Deviation	51			
	CV (%)	15.1			
		Base Electricity (kWh/m²)	Heating-related Electric (kWh/m²)	Cooling-related Electric (kWh/m²)*	Total Electricity (kWh/m²)
Normalized Annual Electricity Consumption	Lowest Consumption	53.2	0.8	0.9	63.3
	Highest Consumption	106.0	20.1	19.2	114.7
	Mean	79.3	7.5	4.1	90.3
	Standard Deviation	11.2	3.7	3.3	11.5
	CV (%)	14.2	49.9	82.5	12.7
		Base Gas (kWh/m²)	Heating-related Gas (kWh/m²)		Total Gas (kWh/m²)
Normalized Annual Gas Consumption	Lowest Consumption	21.9	85.0		141
	Highest Consumption	116.5	283.2		365
	Mean	70.2	175.7		246
	Standard Deviation	22.0	46.5		52
	CV (%)	31.4	26.5		21.0

* Five MURBs didn't show demand for electric cooling in the summer seasons. The results on electric cooling are only reflected in the other 40 MURBs with electric cooling demand.

The base gas consumption has the highest variation of all NACs. The base gas consumptions are in the range of 21.9 kWh/m^2 and 116.5 kWh/m^2, with a mean value at 70.2 kWh/m^2 and standard deviation of 22.0 kWh/m^2. The base gas consumption contributes to domestic hot water production, which is determined by the system efficiency and tenants' behaviours.

The demand for gas heating is influenced by efficiency of mechanical systems, operations, and building envelope. For energy conservation purposes, the building owners can improve gas-heating efficiency by upgrading the HVAC system and improving operation techniques. If the tenants are provided indoor thermal comfort, their behaviour of opening the windows to cool down the apartments in the winter can be minimized. The variations in gas heating efficiency shows that the buildings characteristics and operation can be very different even for buildings built during a similar time periods.

The reference temperature for heating-related electricity consumption is in the range between -6.7°C and 21.7°C with mean value at 12.7°C. This indicates that the electricity consumption is likely to increase when the outdoor temperature is below 12.7°C. On an average, this temperature is much lower than 18.0°C, the widely accepted reference temperature. Since the heating-related electricity consumption can be used to compensate for insufficient gas heating, and possibly increased indoor activity during cold weather. Occupants tend to use more electricity in fall/winter, when the temperature is lower than 18.0°C level with shorter daytime hours.

For cooling-related electricity consumption, the reference temperature is in the 4.4°C to 26.7°C range with mean value at 17.8°C. There are two MURBs that have an extremely low cooling reference temperature at 4.4°C. Because PRISM is a statistical method, those two cooling reference temperature fit well in the linear regression. However, the physical meaning of the low cooling reference temperature in this situation is not clear. The cooling temperature up to 26.7°C can be explained by the use of cooling devices when outdoor temperatures reach an uncomfortably high level.

For gas consumption, the reference temperature is in the range between 12.4°C and 26.8°C with mean value of 19.4°C. In general, the result is similar to the assumption on the fixed reference temperature at 18°C. Only building “4079’ has an extremely high reference temperature at 26.8°C. This MURB is also a relatively energy-efficient building in the benchmarking, at 286 kWh/m^2. It is recommended to further investigate this MURB to account for the high reference temperature. All other MURBs have a reference temperature below 22.2°C.

The mean value of the slopes for heating-related electricity consumption, cooling-related electricity consumption, and gas heating consumption are 65.6, 529.1, and 904 kWh/°C-day, respectively.

It is found that the MURBs with higher heating gas consumptions have higher heating slopes. As displayed in Figure 4-5, although the R^2 for the correlation between heating gas consumption and the heating slope is 0.40, the MURBs especially with high heating gas consumption have the highest heating slope. The high heating slope suggests that those MURBs have poorer insulation compared with its peers.

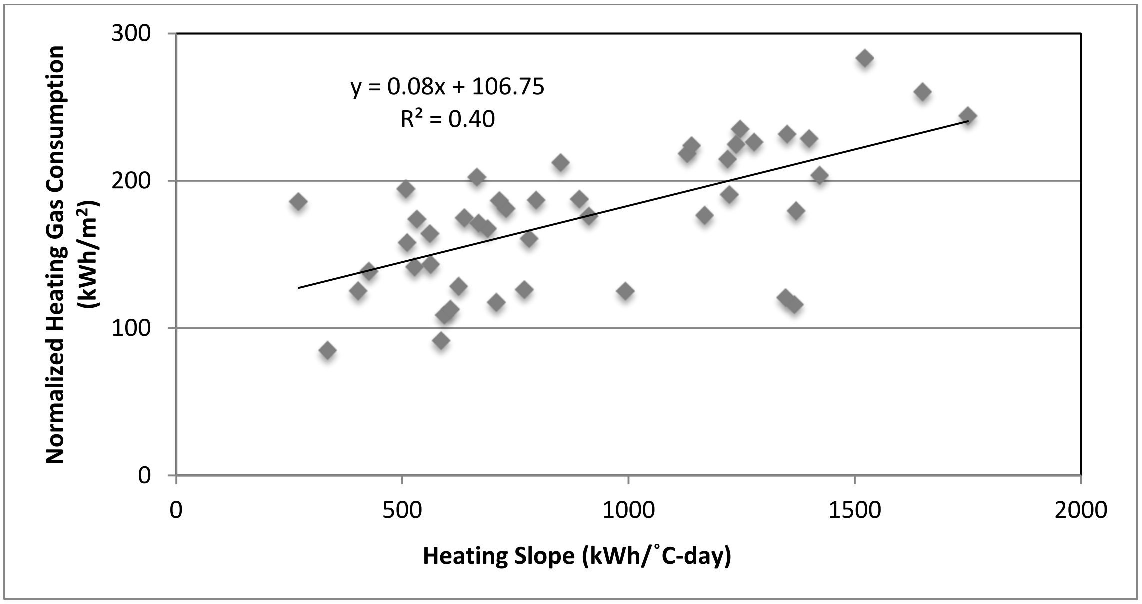

Figure 4-5: Normalized annual heating gas consumption vs. gas heating slope

4.4 Energy Efficiency and Vintage

The relationship between MURB energy efficiency and vintage was examined in this research. As displayed in Figure 4-6, MURBs built during the 1960s and 1970s showed similar energy efficiency. Consumption decreased gradually in late 1970s and 1980s. This correlates with changes to the building code. The Ontario Building Code was first introduced in 1975 with revision in 1983 (Ontario Ministry of Municipal Affairs and Housing, 2010). The improved energy efficiency is a result of improved efficiency of HVAC systems and better exterior envelopes to conform to the new building codes.

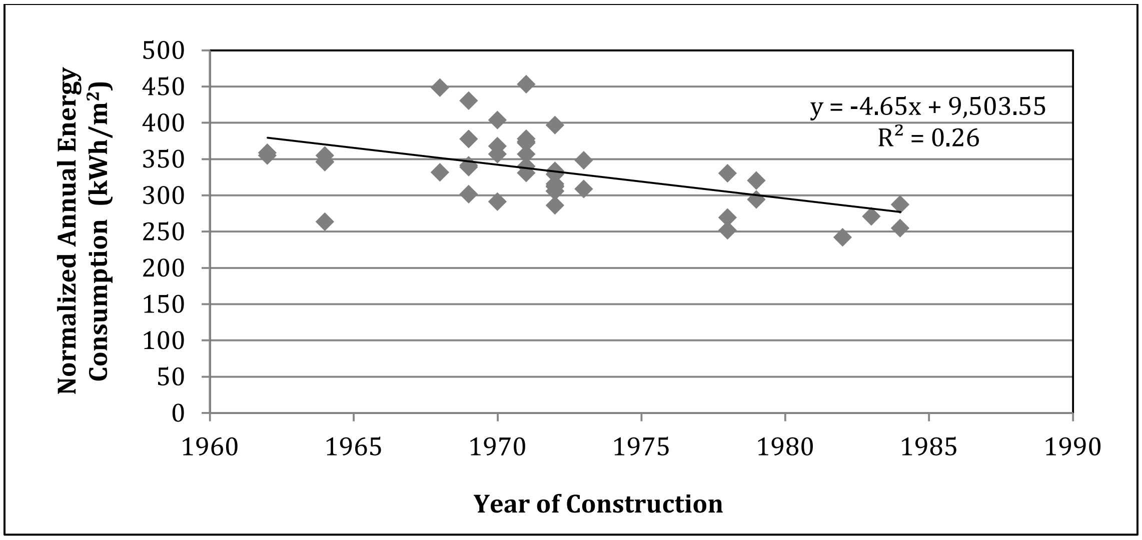

Figure 4-6: Normalized annual energy consumption vs. year of construction

4.4.1 Gas Efficiency and Building Vintage

The normalized annual gas consumption follows a similar pattern as shown in Figure 4-7. The decreasing slope of gas consumption versus year of construction, -4.52, is very close to the slope for overall energy consumption, which is -4.65. This shows that the decreasing energy consumption is caused by improved gas consumption efficiency.

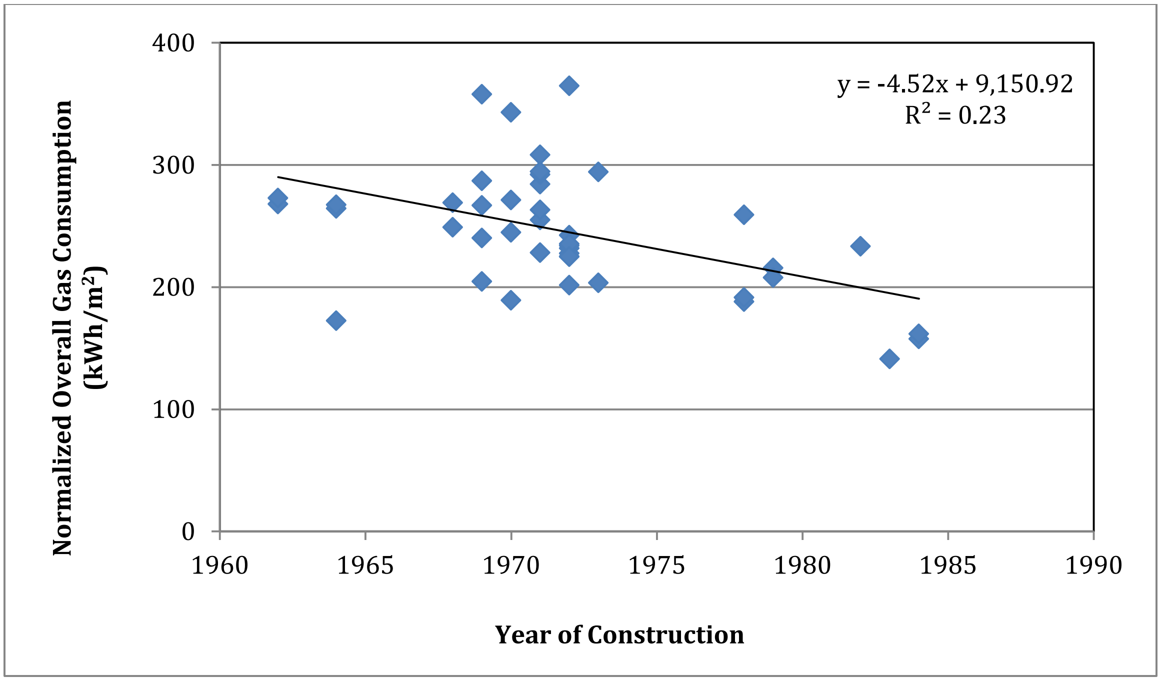

Figure 4-7: Normalized annual overall gas consumption vs. year of construction

The further examination showed that the improved gas efficiency could be explained by the decrease of gas heating consumption. This indicates that the efficiency for space heating by gas has improved while the efficiency for domestic hot water system remains similar. In Figure 4-8, it can be found that the regression slope of normalized heating gas against year of construction, -4.34, is very close to that of overall gas consumption and overall energy consumption, -4.52. For the MURBs built before 1965, building "5934" had a very low heating gas consumption compared with the other five MURBs built in the similar time period. The mean of heating gas consumption of MURBs built before 1965, which are building "3898", "3899", "3244", "3245", and "3243", is 207 kWh/m^2. This number for building "5634" is 109 kWh/m^2, approximately half that of the other MURBs. The demand for the heating-related electricity consumption is the highest in building "5634" when compared with the other five MURBs. The electric heating consumption in "5634" was 10.2 kWh/m^2, which was 57% higher than the mean of the other five MURBs, 6.5 kWh/m^2. The higher electric heating consumption in building "5634" can be explained by occupants' heating demand due to low gas heating consumption. However, the overall performance of building "5634" is more efficient than the other five buildings that were built before 1965.

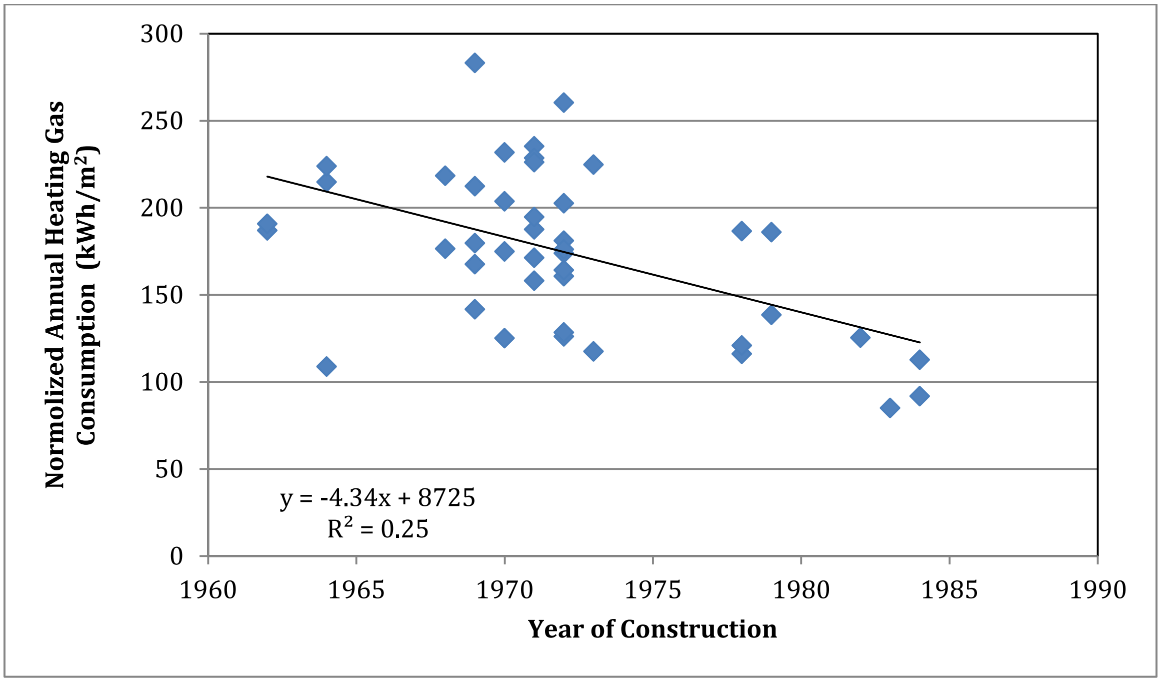

Figure 4-8: Normalized annual heating gas consumption vs. year of construction

The base gas consumptions remain similar for buildings built in different years. As shown in Figure 4-9, the R^2 for the normalized annual base gas consumption and year of construction plot is 0. This indicates that the year of construction does not influence the base gas consumption. Since the use of base gas consumption can be considered as domestic hot water heating, this part of energy use is more likely to be affected by tenants' behaviour.

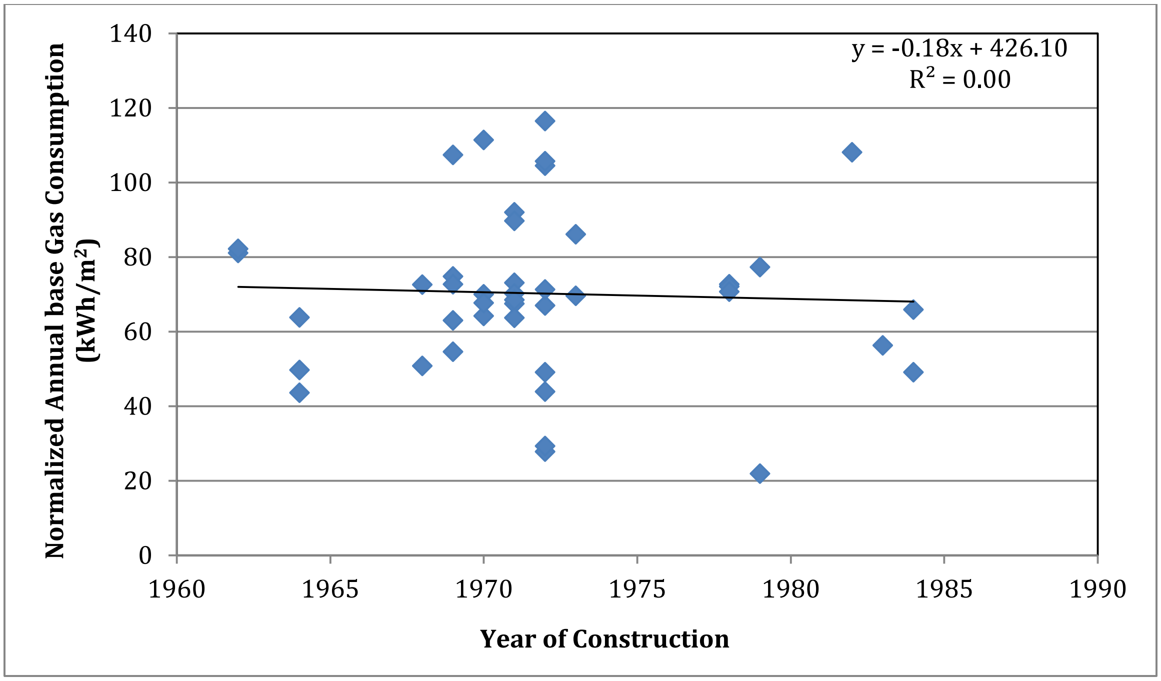

Figure 4-9: Normalized annual base gas consumption vs. year of construction

4.4.2 Electricity Efficiency and Building Vintage

MURBs built more recently showed slightly higher overall electricity consumption as shown in Figure 4-10. Similar trends were found in commercial buildings in Montreal (Zmeureanu & Fazio, 1991). Zmeureanu and Fazio (1991) explained that the larger buildings built in recent decades require more extensive use of electricity for HVAC systems. In this study, the increase in electricity consumption in newer MUBRs is mainly due to increased cooling-related electricity consumption.

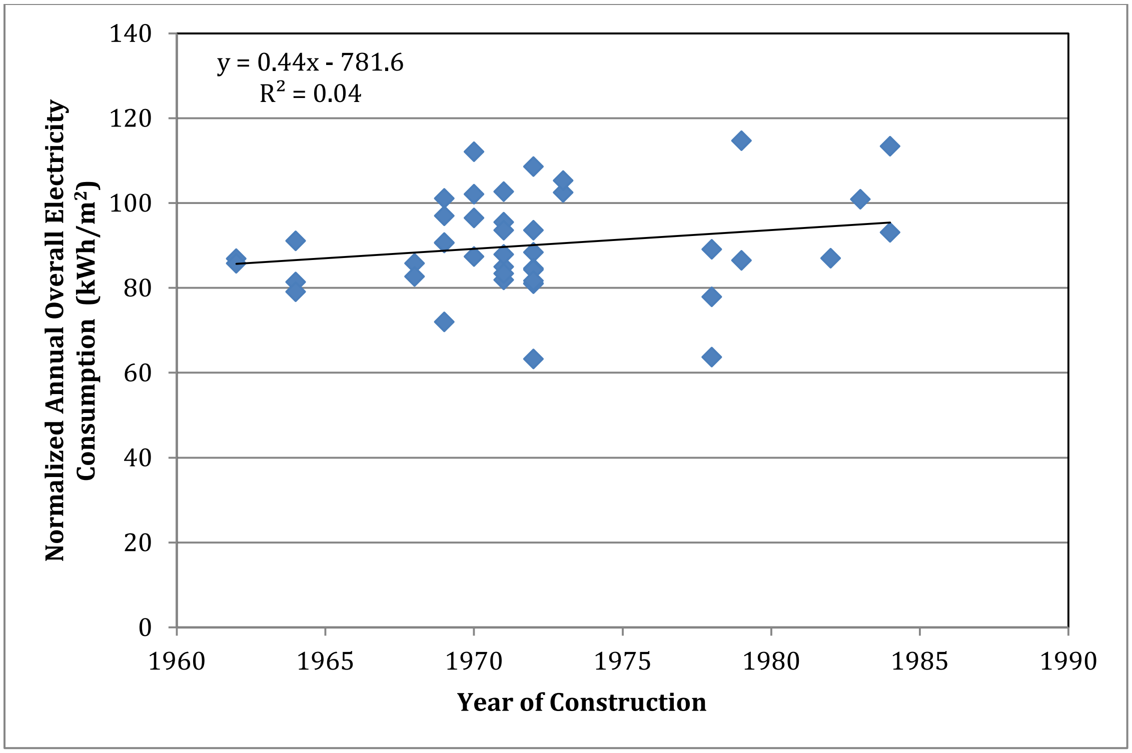

Figure 4-10: Normalized annual overall electricity consumption by year of construction

Figure 4-11 shows that the electric cooling loads are generally higher in MURBs built after 1975. All five MURBs that had no cooling demand were built before 1975. One of the possible explanations is that the electric wiring/infrastructure in the older MURBs would not allow the installation of energy intensive AC systems. Another possible explanation is that the tenants in the newer MURBs have a higher standard for comfort so that a higher percentage of the units installed cooling devices such as window or portable AC.

The management offices of high-rise MURBs have different policies on window AC installation. Some of the MURBs prohibited window AC installations while some charged extra money for units with window AC. It is not confirmed whether the cooling load is solely related to the building age. Further investigations should be done on the differences between the MURBs that may lead to the variation in cooling demand.

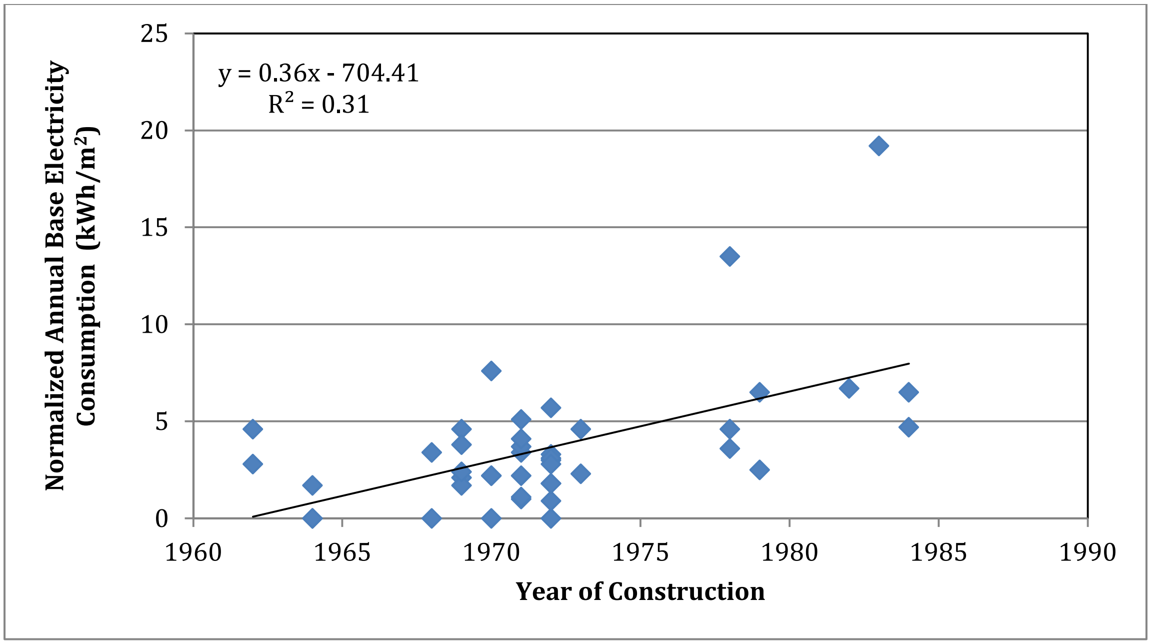

Figure 4-11: Normalized annual cooling-related electricity consumption by year of construction

Base electricity consumption is comprised of lighting, home appliances and plug loads when neither heating nor cooling are required. The upgrading of lighting systems and appliances is ongoing. The plug loads are determined by the possessed appliances and tenants' behaviours. Therefore, the building age does not affect this aspect of energy use, as shown in Figure 4-12. In fact, this energy use is quite uniform in all MURBs.

The same reasoning can be applied to electric heating demand. It can be seen from Figure 4-13 that the demand for electric heating is unlikely to be influenced by building vintage. As the electric heating demand comes from portable heating devices and seasonally related end-uses, this part of energy use is determined by tenants' decisions regarding their appliances and the schedule of use. The MURB itself played little role in electric heating loads.

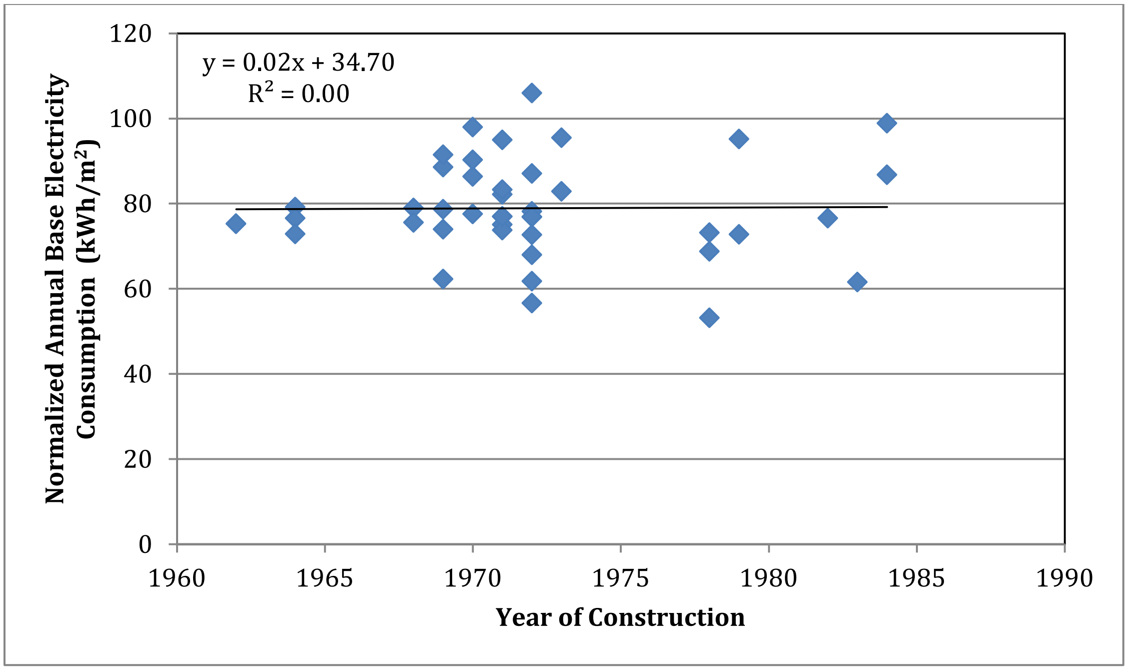

Figure 4-12: Normalized annual base electricity consumption by year of construction

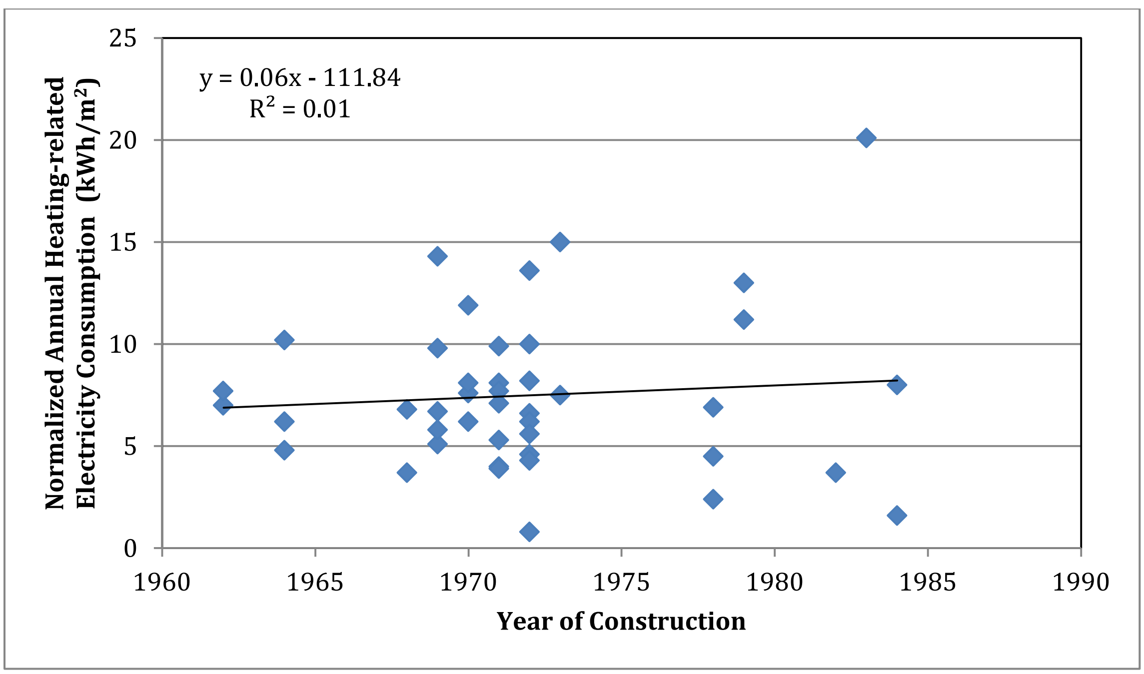

Figure 4-13: Normalized annual heating-related electricity consumption by year of construction

4.4.3 Overall Energy Efficiency Trend in Buildings Built in Different Time Periods

High-rise MURBs that were studied in this research were constructed in four time periods: 1962–1964, 1968–1973, 1978-1979 and 1982–1984. There is at least a 3-year gap between each time period. To evaluate if year of construction affects the energy efficiency in MURBs, the studied MURBs were divided into four sub groups according to the time period of construction. The distribution of MURBs in the four sub-categories is shown in Table 4-2.

Table 4-2: Distribution of MURBs built in different time period

Time Period	Number of MURBs	Mean NAC (kWh/m^2)	Standard Deviation (kWh/m^2)
1962–1964	6	338	37
1968-1973	29	350	45
1978-1979	5	293	33
1982-1984	4	264	20
Overall	44*	336	51

*Only the gas-heated MURBs are studied in this section. One out of the 45 gas-heated MURBs is missing the information on year of construction; thus, was excluded in this discussion.

The F-test was performed to examine if the standard deviations are equal between the sample groups. The result is given in Table 4-3. Each sub sample group was compared with its neighbouring group of newer MURBs. All calculated F values are smaller than the critical value at 95% confidence level. Therefore, the standard variance of each group is equal. This is the premise for a robust T-test.

Table 4-3: F-test for overall energy consumption deviations of each sub sample group

Time Period	F Value – Calculated	F Critical Value – at 95% confidence level	Equal Standard Variance - at 95% confidence level
1962–1964 vs. 1968-1973	1.50	4.50	Yes
1968-1973 vs. 1978-1979	1.82	5.75	Yes
1978-1979 vs. 1982-1984	2.86	9.12	Yes
1962-1964 vs. 1982-1984	1.185	9.01	Yes

The T-test followed the F-test and the results are summarized in Table 4-4. The 1962-1964 group was compared with the 1968-1973 group. The calculated t value is 0.644. The calculated t value is smaller than the t critical values at 95% and 99% confidence levels, which are 2.035 and 2.733, respectively. Therefore, the two groups of samples are not significantly different at 95% and 99% confidence level. This indicates that the energy consumption of MURBs built in 1962-1964 and 1968-1973 are not significantly different, and can be treated as one sample group.

The Same procedure was performed on other groups. The 1978-1979 group is significantly different from 1968-1973 group at 95% confidence level. This means that the sample MURBs built in 1978-1979 have different energy efficiency from the earlier groups. Buildings in 1982-1984 are not significantly different from 1978-1979 group at 95% and 99% confidence level.

To confirm that the year 1975 is a turning point in these MURBs energy efficiency, the studied MURBs were grouped into before 1975 and after 1975. The calculated t value is 4.439, larger than the t critical value at 99% confidence level, 2.698. MURBs that were built before and after 1975 are significantly different at 99% confidence level. Therefore, in the benchmarking, the vintage should be considered in the grouping. Based on the sample of this research, in order to benchmark MURBs with similar peers, MURBs should be divided into groups based on year of construction: 1962-1975 and 1975-1984.

Table 4-4: T-test for overall energy consumption deviations of each sub sample group

Time Period	t Value – Calculated	t Critical Value – at 95% confidence level	t Critical Value at 99% confidence level	Significant at 95% Confidence Level	Significant at 99% Confidence Level
1962–1964 vs. 1968-1973	0.644	2.035	2.733	No	No
1968-1973 vs. 1978-1979	2.694	2.037	2.739	Yes	No
1978-1979 vs. 1982-1984	1.533	2.365	3.499	No	No
Before 1975 vs. after 1975	4.402	2.018	2.698	Yes	Yes

To investigate differences of energy efficiency by vintage, the MURBs in the database are divided into two groups: 35 built before 1975 and nine built after 1975. The results are shown in Table 4-5. The mean energy consumption in MURBs built after 1975 was 280 kWh/m^2. Compared with that of MURBs built before 1975, the energy consumption drops 19% from 348 kWh/m^2.

Table 4-5: Overall energy consumption of MURBs built before and after 1975

Group	Mean Energy Consumption Overall (kWh/m^2)	Lowest Energy Consumption Overall (kWh/m2)	Highest Energy Consumption Overall (kWh/m2)	STDEV (kWh/m2)	CV (%)
Before 1975	348	264	453	43	12
After 1975	280	242	331	31	11
Difference	-19%	-8%	-27%	-	-

The energy consumption of the top performer in the before 1975 group, building "5634", is only 8% higher than that of the after 1975 group. This can be a signal to the older MURBs that it is empirically possible to improve energy efficiency of the older buildings to a much higher level. It is highly recommended to study building "5634" on its energy conservation strategy. The lesson learned from this building can be valuable to the owners of other buildings that were built before 1975.

It can be concluded that the construction year of 1975 is the turning point for energy efficiency in Ontario high-rise MURBs. It is believed that the implementation of the first building code in Ontario had positive effects on the energy efficiency in high-rise MURBs.

4.4.4 Energy Efficiency Changes by Vintage

Knowing that the overall energy efficiency had a substantial improvement in 1975, the statistical significance tests were performed to support the observations in Section 4.4.1 and 4.4.2. The F-test and T-test results for end-use energy consumption are displayed in Appendix E.

The F-test proved that equivalent variance were true except for the following groups: 1) group 1962-1964 and group 1968-1972, base electricity consumption and total electricity consumption; 2) group 1968-1972 and group 1978-1979, total gas consumption; and 3) group 1978-1979 and group 1982-1984, base gas consumption. The mentioned situations will not be further discussed because when variances are unequal, errors of the T-test become inflated to various degrees and will be invalidated.

The following energy consumptions are found to be different to a statistically significant degree at both 95% and 99% confidence levels:

- MURBs built before and after 1975: cooling electricity consumption, heating gas consumption, and overall gas consumption
- MURBs built in 1968-1973 and 1978-1979: heating gas consumption
- MURBs built in 1978-1979 and 1982-1984: overall gas consumption

The changes of energy efficiency at the 1975 turning point were the result of increased cooling electricity consumption and decreased heating gas consumption. The results are given in

Table 4-6 and 4-7. The electric cooling demand increased 117%, and the gas heating demand decreased by 33%.

Table 4-6: Electric cooling consumption in MURBs built before and after 1975

Group	Mean Electric Cooling Consumption (kWh/m^2)	Lowest Electric Cooling Consumption (kWh/m^2)	Highest Electric Cooling Consumption (kWh/m^2)	STDEV (kWh/m^2)	CV (%)
Before 1975	2.9	0.0	13.5	2.5	87
After 1975	6.3	6.3	19.2	5.1	80
Difference	117%	-	42%	-	-

Table 4-7: Gas heating consumption of MURBs built before and after 1975

Group	Mean Heating Gas Consumption (kWh/m^2)	Lowest Heating Gas Consumption (kWh/m^2)	Highest Heating Gas Consumption (kWh/m^2)	STDEV (kWh/m^2)	CV (%)
Before 1975	187	109	283	40	22
After 1975	124	85	186	30	24
Difference	-33%	-22%	-34%	-	-

4.4.5 Ratio of Electric Energy to Total Energy Use

Section 4.4.1.2 argued that the electricity demand increased in the newer MURBs while the gas demand decreased. For the 45 gas-heated MURBs with the information on year of construction, the mean value for electrical-to-total energy ratio is 0.27.

The F-test and T-test were applied to the four MURBs groups by vintage as described in section 4.4.1.3. It is found that the ratio remains uniform until year 1982. The MURB group 1978-1979 is significantly different from MURB group 1982-1984. This means that the newer MURBs use more electricity and less gas relatively. Based on this observation, the MURBs are grouped into MURBs constructed in 1962-1979 and in 1982-1984. The ratio of electric energy to total energy use for the two groups is 0.26 and 0.39 respectively. The MURBs built in 1982-1984, on average have a 40% higher ratio of electric energy to total energy use than MURBs built in 1968-1979. This can be explained by the fact that the newer MURBs have a higher electricity demand for HVAC, lighting and appliances, while the gas consumption is more efficient due to improved building envelopes and mechanical equipment.

4.5 Energy Efficiency and Building Volume

The relation between energy efficiency and building volume was examined. The volume of the building determines the amount of heating needed in the MURB. The high-rise MURBs in Toronto have similar floor height. The volume of a MURBs is the gross floor area multiple by floor height. Since the floor height was not provided, it was assumed to be 3 meter.

The result shows that the volume of the MURB plays a small role in the energy performance of the MURB. Illustrated in Figure 4-14, the normalized annual overall energy consumption is poorly correlated with the building volume. Thus, it can be inferred that the volume of the studied MURBs is not a major factor to influence the overall energy efficiency of the building.

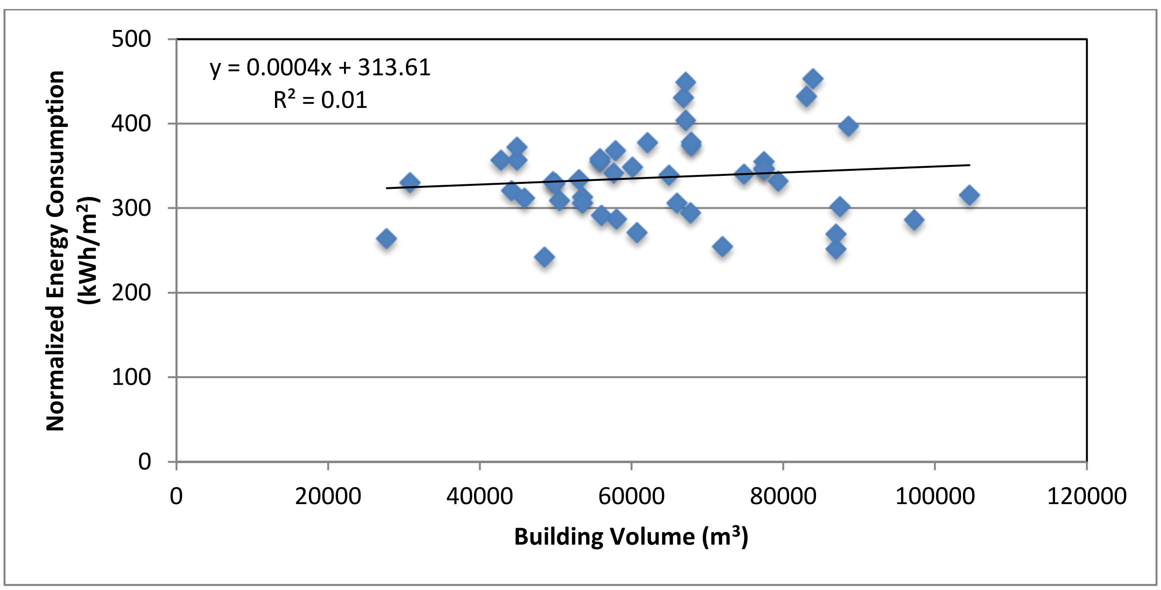

Figure 4-14: Normalized annual gross energy consumption by square meters vs. builing volume

The relation between electricity consumption and building volume is weak but there is a trend that the larger MURBs use less electricity per area s. It can be seen in Figure 4-15, 4-16 and 4-17 that larger MURBs consume less electricity for base, heating-related, and cooling-related activities, which lead to the same trend for the overall electricity consumption. As shown in Figure 4-18, the R^2 for normalized annual electricity consumption and building gross floor area is 0.17. This figure confirms that the electricity consumption is lower in the larger MURBs, although the relation is weak.

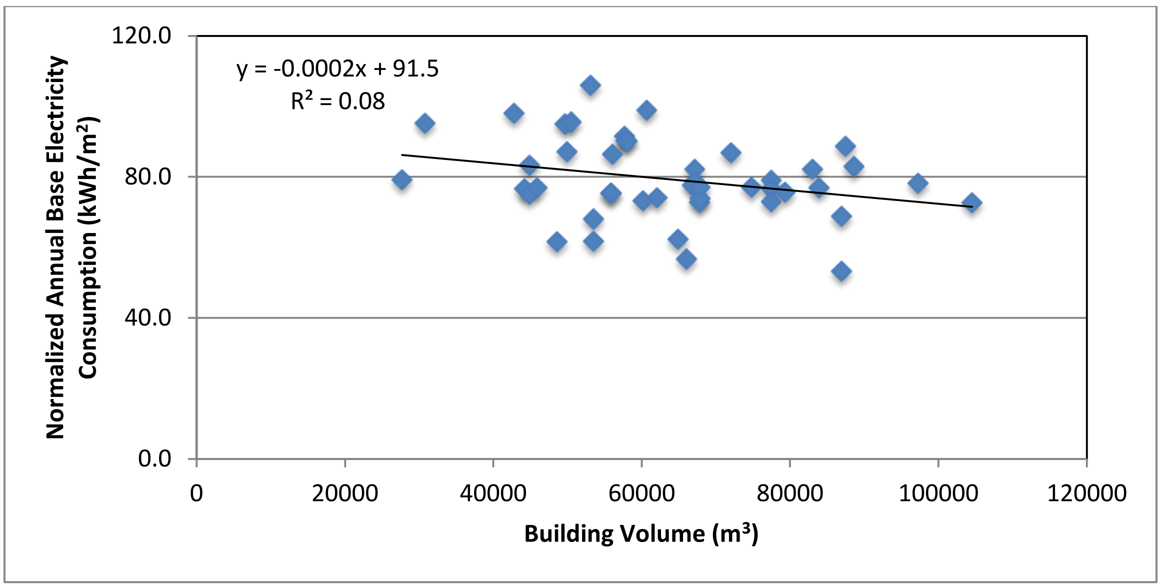

Figure 4-15: Normalized annual base electricity vs. building volume

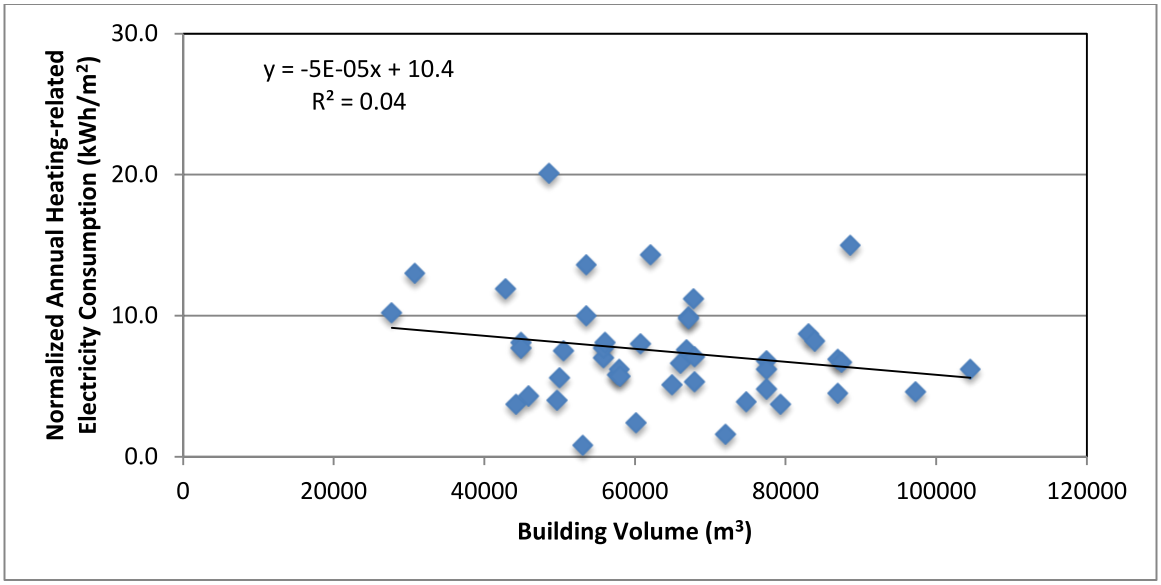

Figure 4-16: Normalized annual heating-related electricity consumption vs. building volume

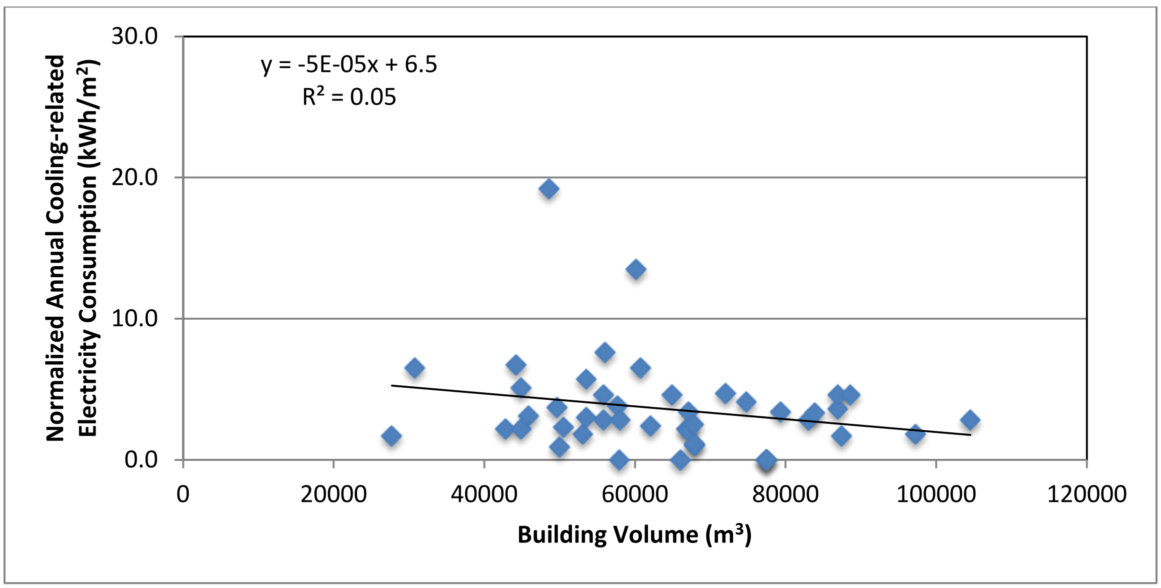

Figure 4-17: Normalized annual cooling-related electricity consumption vs. building volume

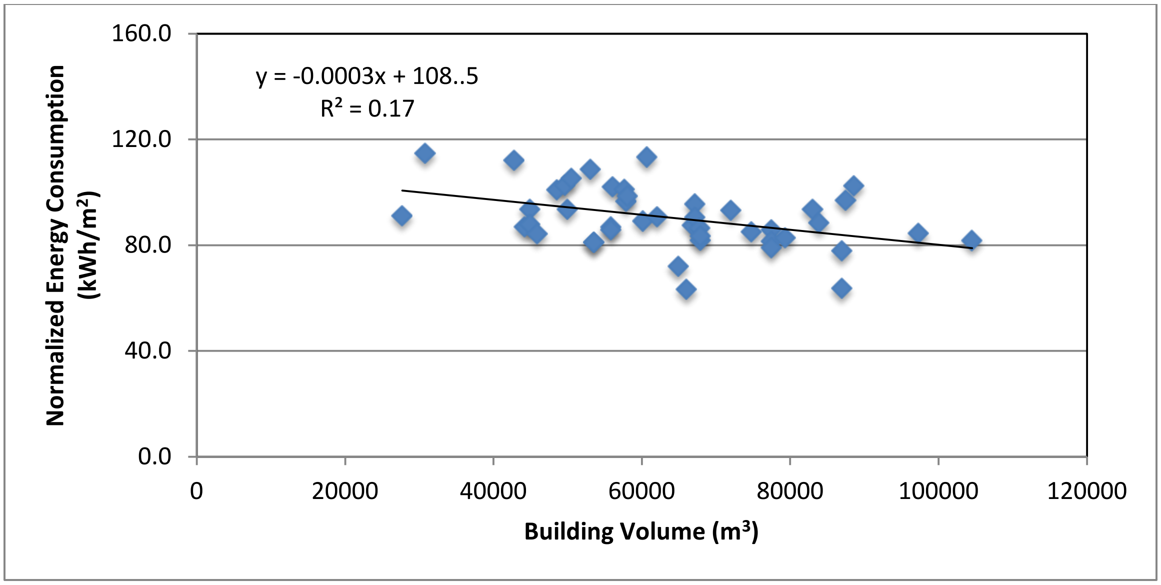

Figure 4-18: Normalized annual total electricity consumption vs. building volume

Figure 4-19 shows the relation between normalized annual base gas consumption and building gross floor area. The base gas consumption scatters with no obvious pattern.

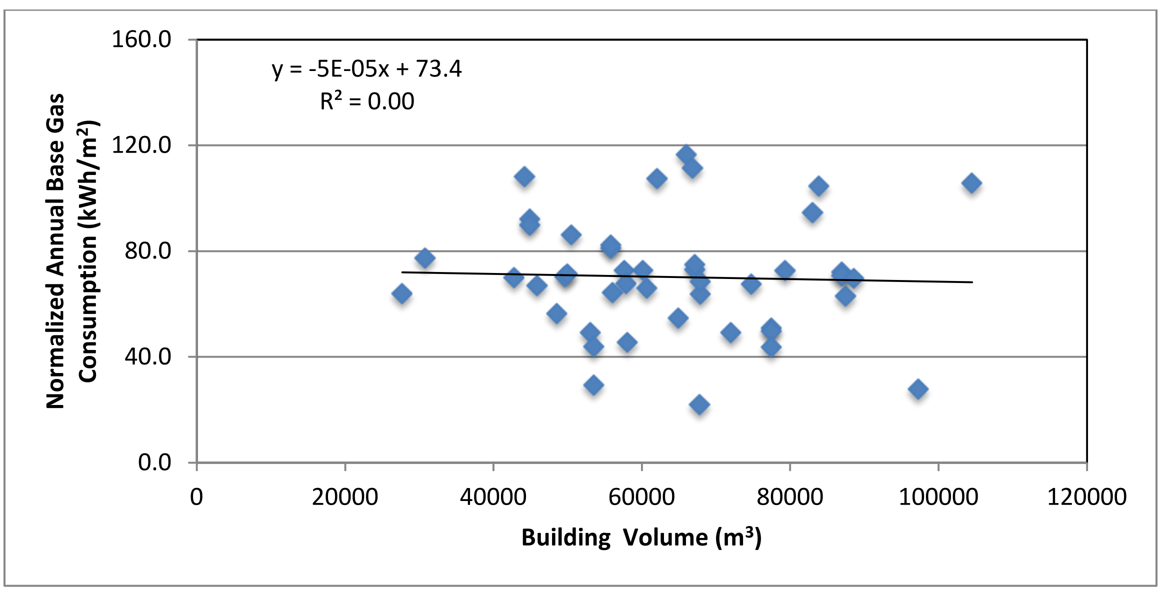

Figure 4-19: Normalized annual base gas consumption vs. building volume

The heating gas consumption increases slightly with the building gross area. This trend is also observed in the overall gas consumption. As shown in Figure 4-20 and Figure 4-21, the heating related gas consumptions and overall gas consumptions are higher in the larger MURBs.

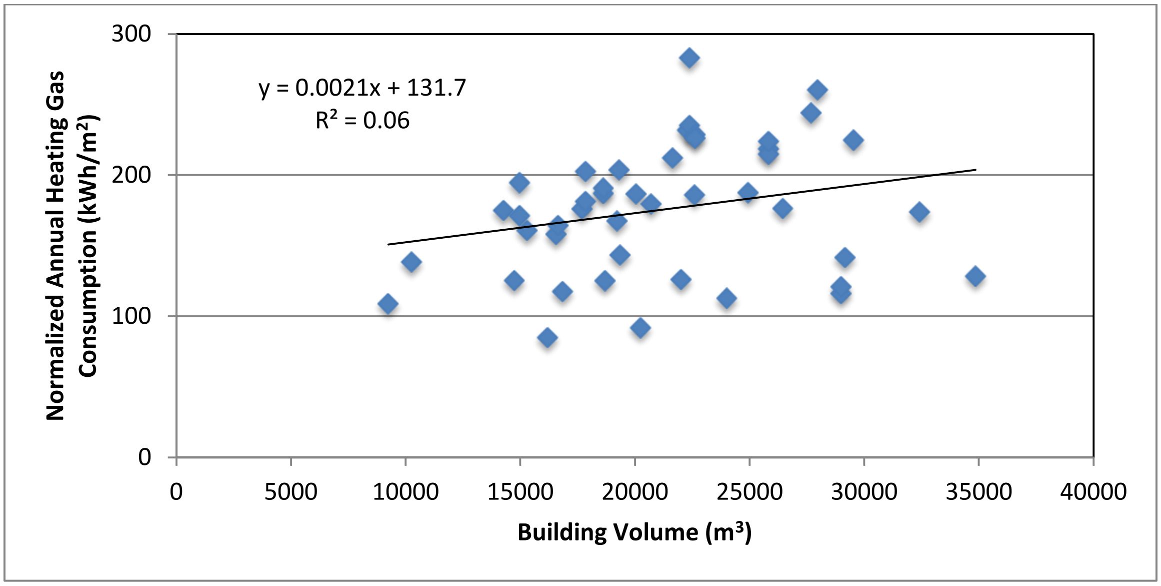

Figure 4-20: Normalized annual heating gas consumption vs. building volume

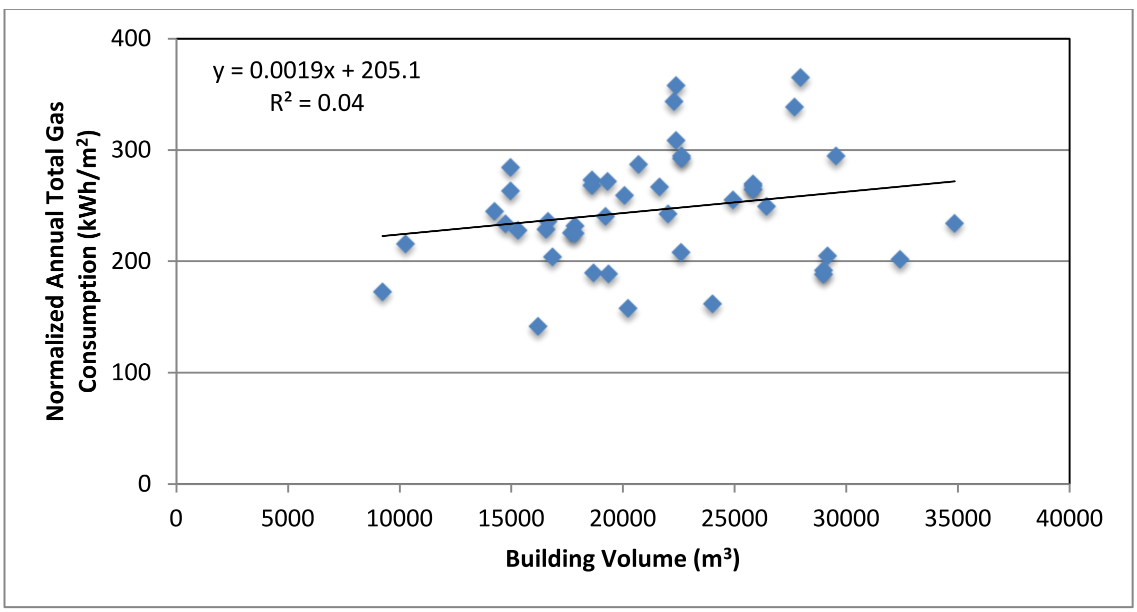

Figure 4-21: Normalized annual total gas consumption vs. building volume

4.6 Energy Efficiency and Number of Unit

Energy efficiency in high-rise MURBs is unlikely to be affected by number of units. The number of units in the MURB can represent the number of households. Usually, the number of households can reflect the number of stove and oven, fridge, microwave oven etc. in the MURB, because usually each unit contains one appliance of each kind.

Figure 4-22 shows the relation between normalized annual energy consumption and number of units. The number of units has little impact on the energy efficiency. The MURB with the highest number of units, 439, has an energy efficiency of 302 kWh/m^2, compared with the MURB with the fewest units, 137, which has an efficiency of 312 kWh/m^2. Given the R^2 is close to 0, it can be inferred that the number of units have little impact on the annual energy consumption.

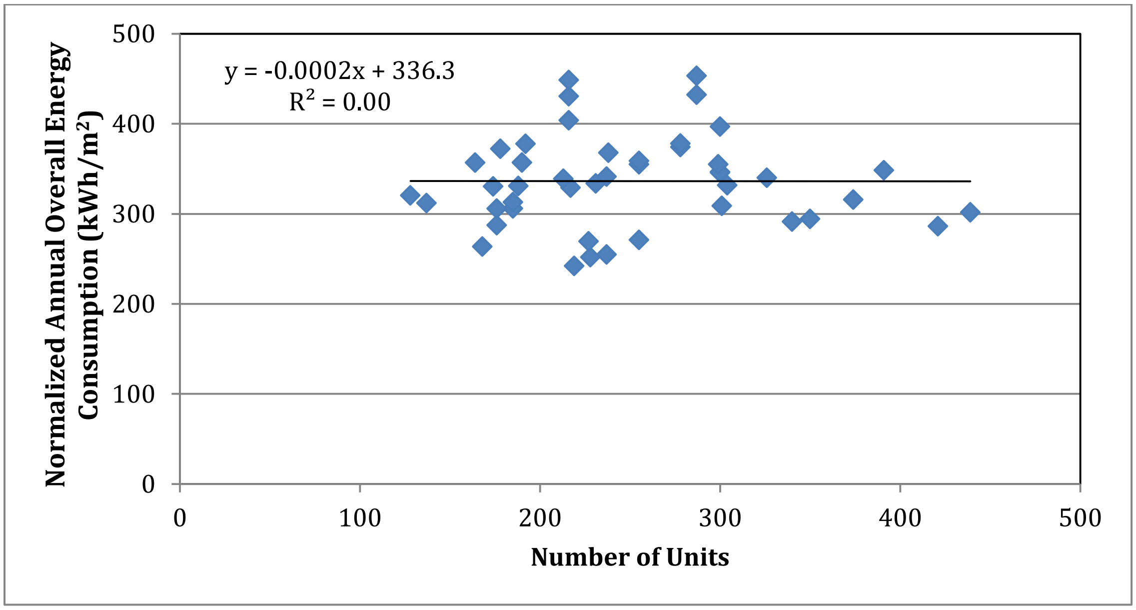

Figure 4-22: Normalized annual overall energy consumption vs. number of unit

The relation between different end-uses and number of units are shown in Figure 4-23, 4-24, 4-25, 4-26, 4-27, 4-28, and 4-29. All linear regressions have very low correlations. Similar conclusions are drawn from the break-down energy use: the number of units has little impact on neither electricity (base, heating-related and cooling-related) nor gas (heating related and base) consumption.

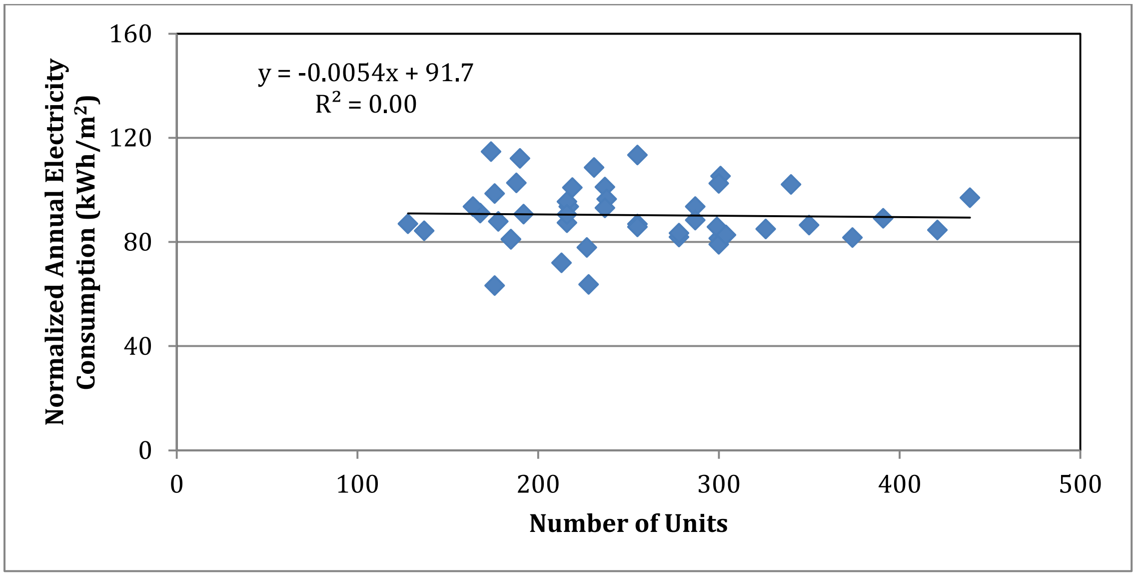

Figure 4-23: Normalized annual electricity consumption vs. number of units

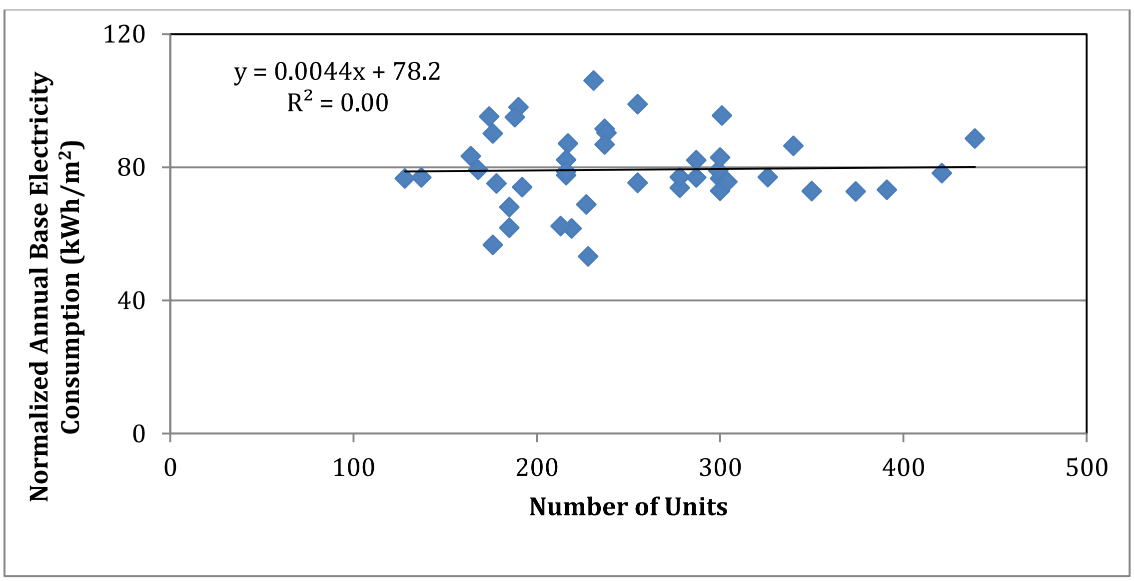

Figure 4-24: Normalized annual base electricity consumption vs. number of units

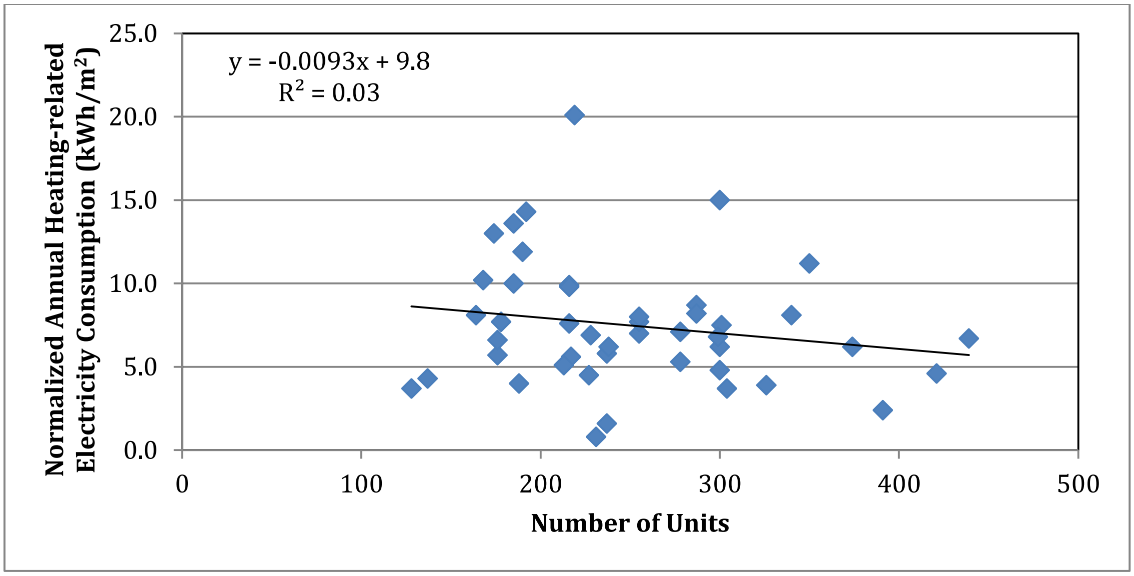

Figure 4-25: Normalized annual heating-related electricity consumption vs. number of units

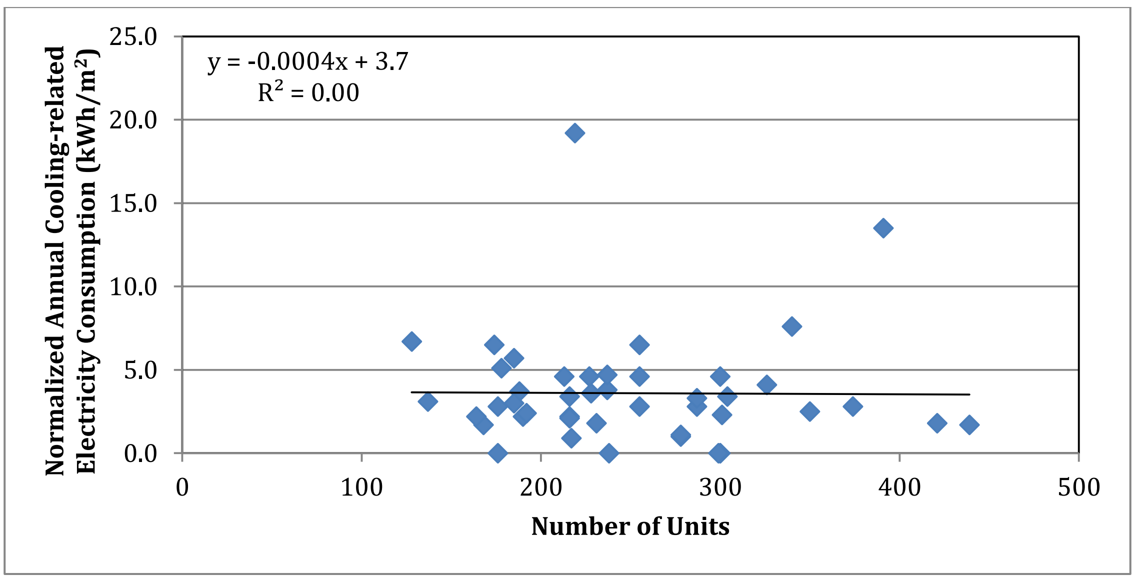

Figure 4-26: Normalized annual cooling-related electricity consumption vs. number of units

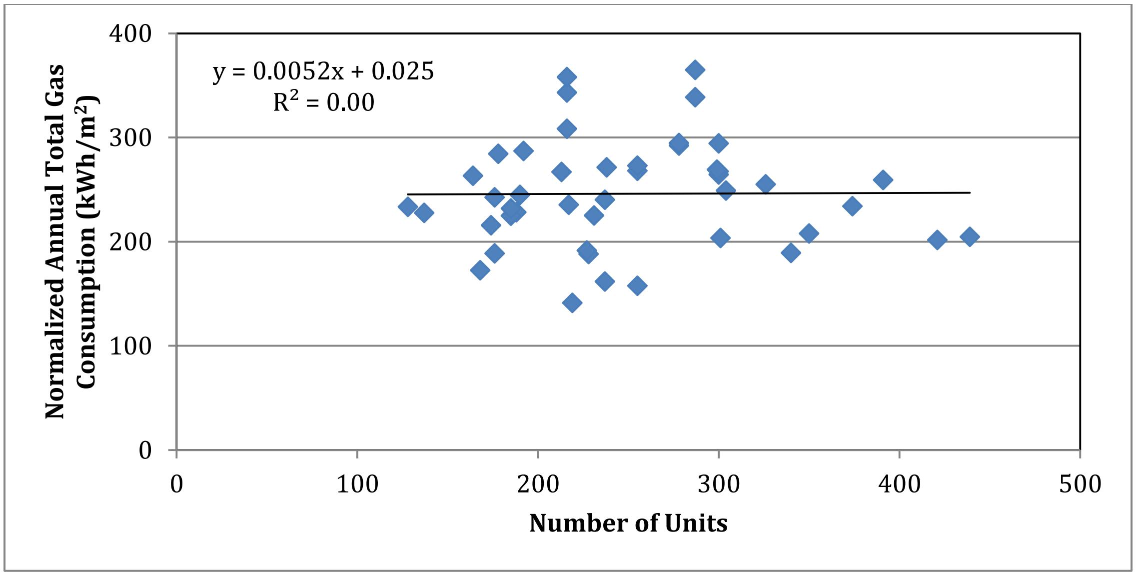

Figure 4-27: Normalized annual total gas consumption vs. number of units

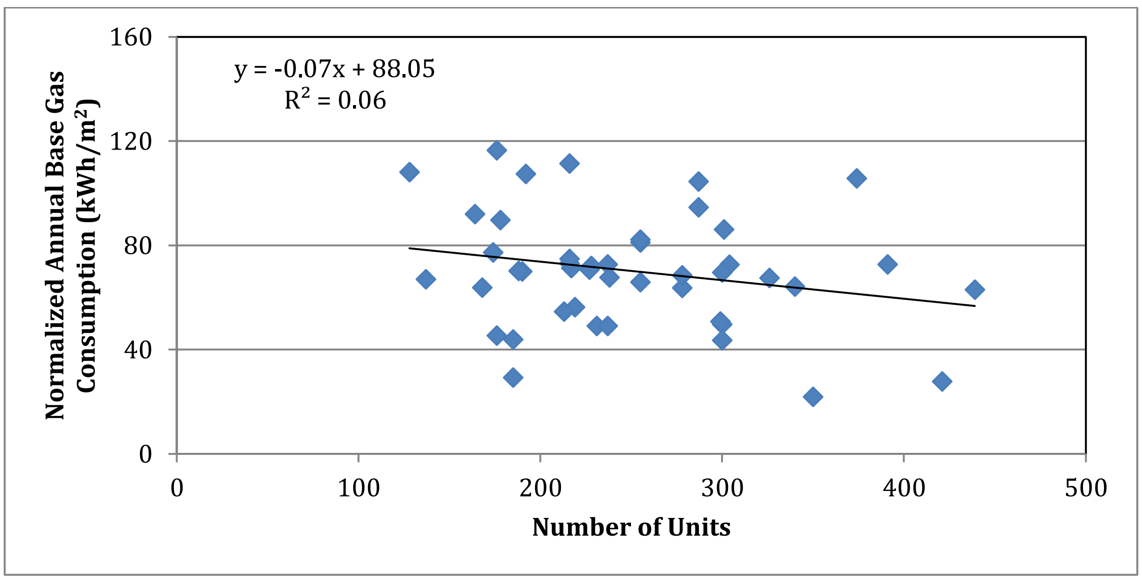

Figure 4-28: Normalized annual base gas consumption vs. number of units

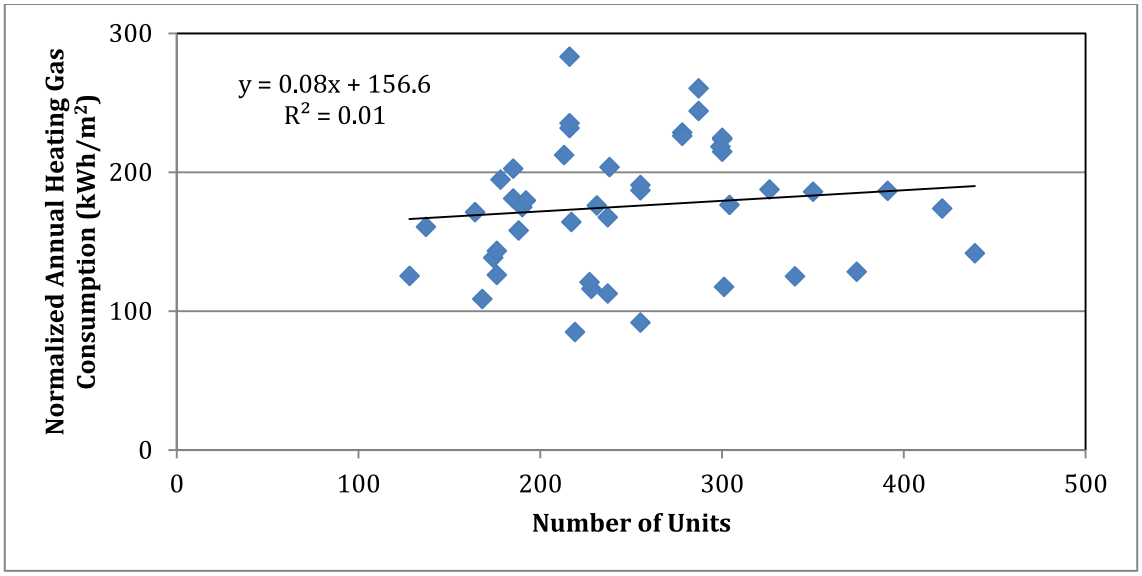

Figure 4-29: Normalized annual heating gas consumption vs. number of units

4.7 Energy Efficiency and Occupancy

Because the purpose of energy use is to support the comfort of persons occupying these MURBs, it is vital to know how many people live in the MURB; in other words, the occupant density of the building. However, building occupancy data is not available because building management offices do not require tenants to provide information on the number of occupants in their households. As an alternative, the following discussion will use the estimated number of bedrooms to represent the total building occupancy. The estimated number of bedrooms was calculated as the total number of bedrooms in the MURB multiplied by the suite occupancy rate. The monthly occupancy rates from January 2009 to September 2011 were provided for 35 MURBs, which will be used for the following discussion.

The correlation between normalized annual gross energy consumption by area and the number of bedrooms is poor. As shown in Figure 4-30, the R^2 for the correlation is zero. This indicates that the number of bedrooms in the studied MURBs does not affect the energy consumption by area.

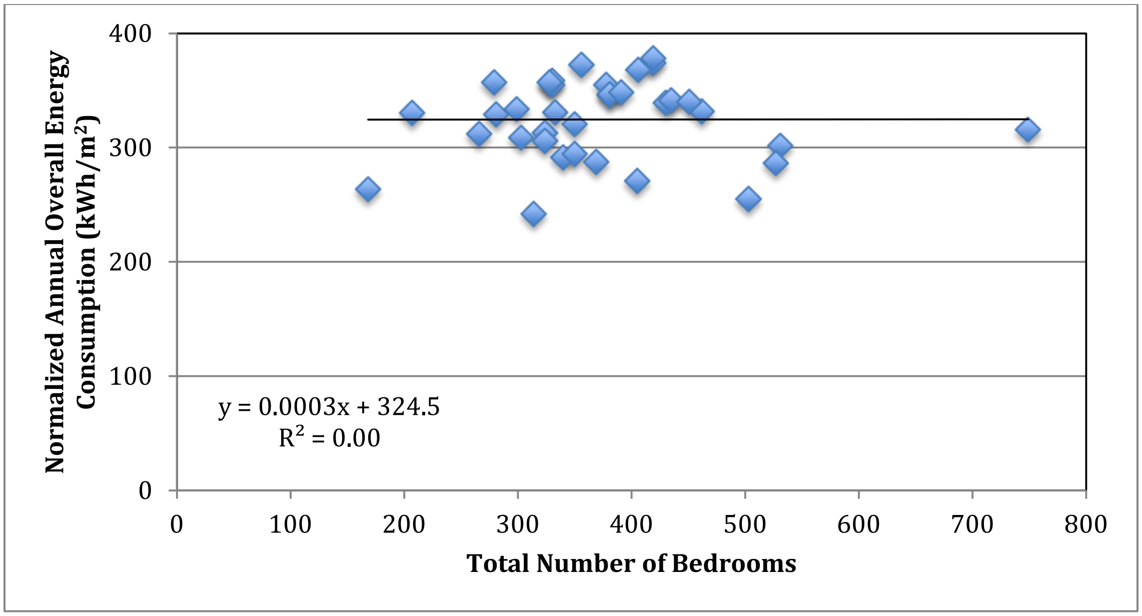

Figure 4-30: Normalized annual overall energy consumption vs. total number bedrooms

The occupancy rate of each MURB ranges from 90.5% to 99.7% between January 2010 and September 2011. The mean occupancy rate of all MURBs is 97.0%, indicating the studied MURBs are well occupied. It is unknown what types of units were vacant; thus, the number of occupied bedrooms is estimated by using the occupancy rate multiplied by the total number of bedrooms.

The relation between normalized annual overall energy consumption and estimated number of bedrooms is illustrated in Figure 4-31. Similar to the correlation in Figure 4-30, the R^2 it is still too low to determine a relation. Therefore, when the occupancy rate is high, the number of occupied bedrooms is unlikely to influence the total energy consumption.

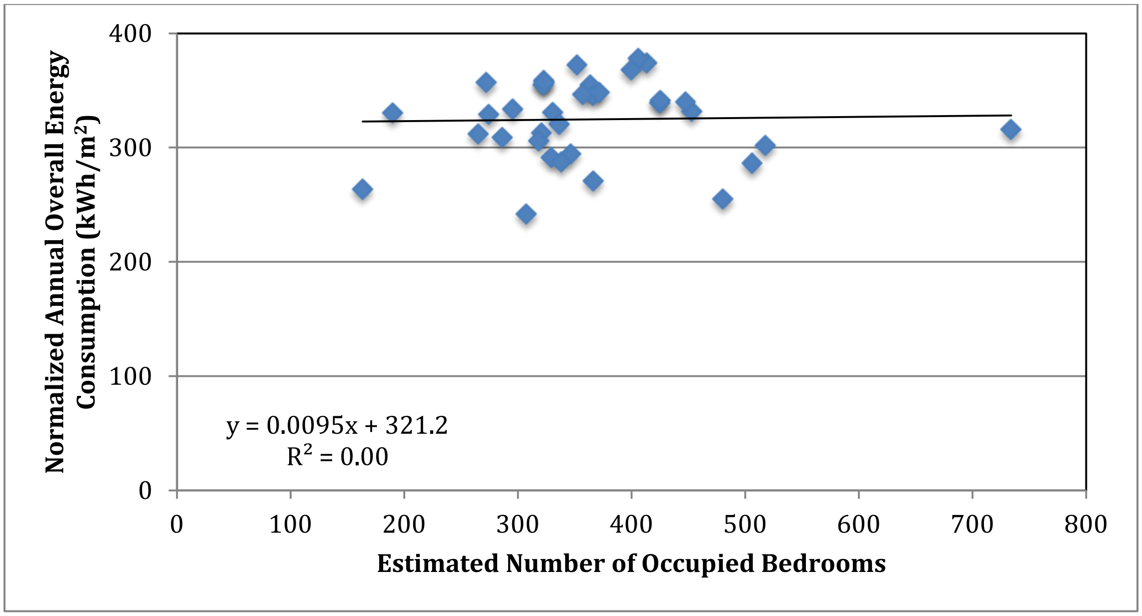

Figure 4-31: Normalized annual overall energy consumption vs. estimated number of occupied bedrooms

The correlation between each end-use energy consumption and estimated number of occupied bedrooms is not noticeable, apart from heating related electricity consumption. Figure 4-32 illustrated the relation between normalized annual heating-related electricity consumption and estimated number of occupied bedrooms. The MURBs with annual heating-related electricity consumption above 10.0 kWh/m^2 tend to have fewer occupied bedrooms. Since the parameter of number of occupied bedrooms represents the number of people who live in the MURB, it can be inferred that the MURB with fewer tenants tends to use more heating-related electricity per area.

In Figure 4-32, it is found that building 5964 with 308 estimated occupied bedrooms has a very high demand for heating-related electricity compared to buildings with similar number of estimated occupied bedrooms. The annual heating-related electricity consumption for this building "5964" is 20.1 kWh/m^2. This building also has very high cooling-related electricity consumption, as discussed in Section 3.4.1. The feature of this building is that the unit size tends to be small and overall energy efficiency is high. It can be inferred that the tenants in this building tended to control the thermal comfort by themselves more than tenants in other MURBs in this research.

A similar trend is found in energy consumption and total number of bedrooms. However, studied MURBs have similar occupancy rates. The number of estimated occupied bedrooms in the MURBs is close to the number of total bedrooms. Based on the data in this research, it is unknown if the energy consumption is affected by the total number of bedrooms in the MURB or occupied bedrooms only.

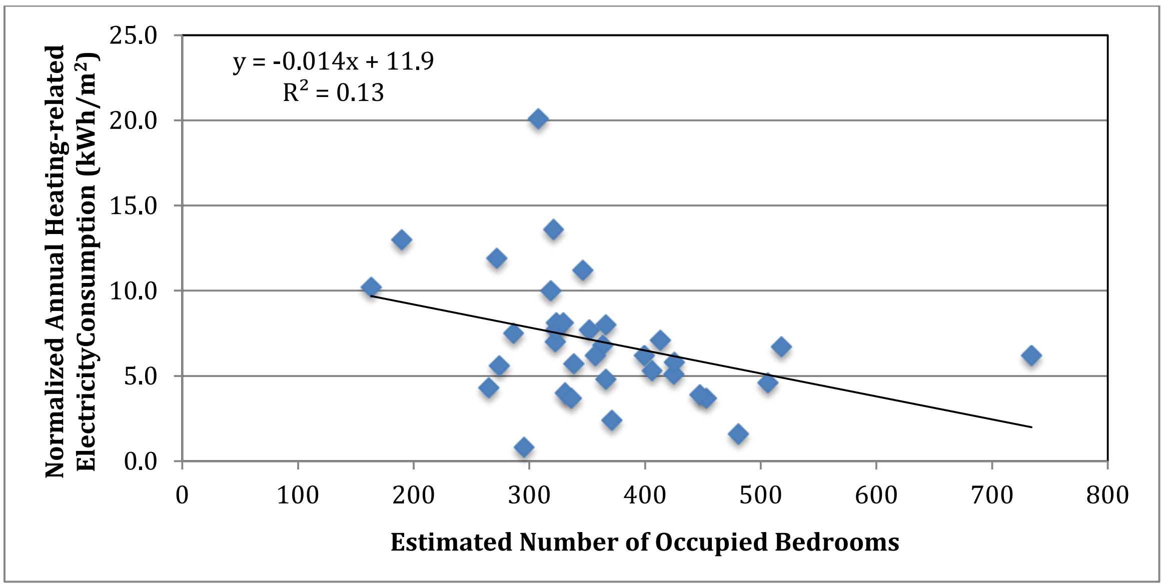

Figure 4-32: Normalized annual heating-related energy consumption vs. estimated number of occupied bedrooms

4.8 PRISM Result: Using Multiple-years vs. 1-year Utility Bills

The PRISM benchmarking results using 1-year of utility bills are slightly different than using multiple-years. Table 4-8 gives the PRISM NAC based on multiple-years of past bills and on a single year. There are 24 MURBs that have post-retrofit utility bills representing multiple years. Among the 24 MURBs, 15 of them have NAC differences in the range of ±3%, four of them within ±3-5%, and five in the ±5-10% range. The PRISM is a statistical empirical method; thus the error comes from the statistical estimations. The small difference in calculated NACs gives consistent results, regardless of multiple-years or 1-year of utility bills data.

Table 4-8: Comparison of PRISM estimated NAC based on multiple-year and 1-year utility bills

ID	PRISM Multiple Year NAC (kWh/m^2)	PRISM 1-Year NAC (kWh/m^2)	Difference	ID	PRISM Multiple Year NAC (kWh/m^2)	PRISM 1-Year NAC (kWh/m^2)	Difference
3145	-	374	-	4358	-	357	-
3146	-	378	-	4359	-	372	-
***3242**	339	340	0.3%	4741	-	321	-
***3243**	355	335	-5.8%	*4790	331	330	-0.3%
***3244**	346	360	4.0%	5521	-	291	-
***3245**	347	364	5.1%	5528	-	349	-
***3477**	357	358	0.0%	*5549	294	289	-1.9%
***3496**	341	341	0.0%	5634	-	264	-
***3497**	309	315	2.1%	*5643	271	275	1.4%
***3516**	368	402	9.2%	*5645	287	280	-2.5%
3624	-	316	-	*5674	255	248	-2.7%
3798	-	331	-	5964	-	242	-
***3815**	312	317	1.6%	*9710	404	401	-0.6%
3898	-	355	-	*9711	449	455	1.4%
3899	-	359	-	*9712	453	429	-5.4%
3983	-	332	-	*9713	397	390	-1.8%
4018	-	340	-	*9714	431	398	-7.6%
***4053**	302	312	3.4%	*9715	432	434	0.3%
4077	-	329	-	*BLD5	306	306	0.0%
4078	-	334	-	*Bldg1	252	264	4.8%
4079	-	286	-	Bldg2	-	270	-
4115	-	313	-	*Bldg3	378	376	-0.4%
4116	-	306	-				

* Normalized annual energy consumption calculations are slightly different when using 1-year bills and multiple-year utility bills.

The highest difference is 9.2% in building "3516". The R^2 in the multiple-year utility bill analysis is 0.77 for electricity and 0.90 for gas consumption, while in the 1-year analysis, the R^2 are 0.93 for electricity and 0.84 for gas. The R^2 in both calculations meet the reliability requirement of the method: $R^2>0.7$. An explanation for the significant difference is that building "3516" has a gradually small change in energy consumption over time. The year-by-year difference in NAC is below 5%. The difference can be a system error rather than improved energy efficiency from retrofits. This is the weakness of PRISM. When analyzing MURBs with slightly changing annual energy consumption, it is not possible to determine if a retrofit was implemented in the MURB or it was due to the randomness of tenants' behaviour. In such a situation, further investigation of changes that were made in the MURB should be performed.

4.9 Energy Benchmarking by Simple Ratio Weather Normalization and Portfolio Manager

MURBs are benchmarked using SRWN and PM. PM provide benchmarking results based on 1 calendar year (12 calendar months) of utility bills. In order to be consistent on the input data, the latest available 12-month utility data were used for benchmarking. Unlike PRISM, SRWN and PM only provide the overall energy consumption results. Therefore, the breakdown results on end-use are not available for discussion.

4.9.1 Benchmarking Result: SRWN vs. PRISM

The annual energy consumption benchmarked using SRWN method is within the range of 254 and 463 kWh/m^2 with a standard deviation of 49 kWh/m^2. Compared with PRISM, the result differences are between -3.1% and 16.3%. The mean difference of each MURB is 3.7%, with a standard deviation of 4.2%. SRWN benchmarking tends to overestimate the results compared with PRISM. Building "Bldg 5" has the greatest difference at 16.3%. The utility bills of this building contain one estimated reading in the winter season (November). This estimated reading is 42% higher than the monthly reading in the same month the year before. This can be the reason for the overestimation.

Benchmarking results calculated by SRWN method are compared with PRISM results as shown in Figure 4-33. The correlation has a good fit with an $R^2 = 0.93$. The slope is 0.96 and with an intercept of 23.92. If the two methods have good consistence, the slope should be close to 1 with a R^2 close to 1, as well as an intercept close to zero.

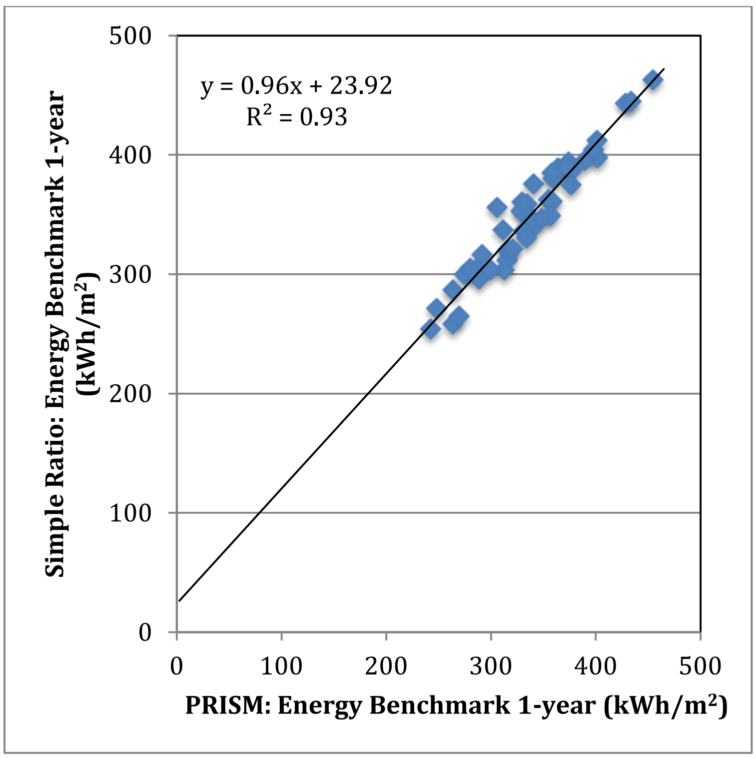

Figure 4-33: Benchmarking result using 1-year bill comparison: SRWN vs. PRISM

For the energy consumption range of studied MURBs, SRWN method is likely to overestimate the result. Since the energy benchmark calculated by PRISM range from 242-455 kWh/m^2 (based on 1-year utility bills), based on the correlation, SRWN overestimates the result by 6–14 kWh/m^2. The difference is within 1.3% - 5.8% range, and the higher the consumption, the closer the results.

SRWN is the simplest method compared to PRISM and PM. SRWN is ideal for users who have limited expertise and/or time to obtain relatively accurate energy benchmarking. However, the error of the results may increase when utility bills contains inappropriate estimated readings.

4.9.2 Benchmarking Result: PM vs. PRISM

The PM benchmarking for annual energy consumption of MURBs is within the range of 239-449 kWh/m^2, with a standard deviation of 51 kWh/m^2. Compared with PRISM, the result differences are between -8.1% and 4.8%. The mean value of difference of each MURB is 0.6%, with a standard deviation of 3.1%. SRWN benchmarking tends to overestimate the results compared with PRISM. Building “4359” has the greatest difference at -8.1%. The utility bills of this building contain one estimated reading for August. This can be the reason for the underestimation.

The comparison of PM and PRISM benchmarking results is illustrated in Figure 4-34. The R^2 = 0.96, which indicates a good correlation. The slope of PM and PRISM results correlation is 1.01 with an intercept of -4.54. If those two methods have good consistence, the slope should be close to 1 with a R^2 close to 1. The assumption that the daily consumption remains constant within one billing cycle seems to have minimum effect on the weather normalization benchmarking result.

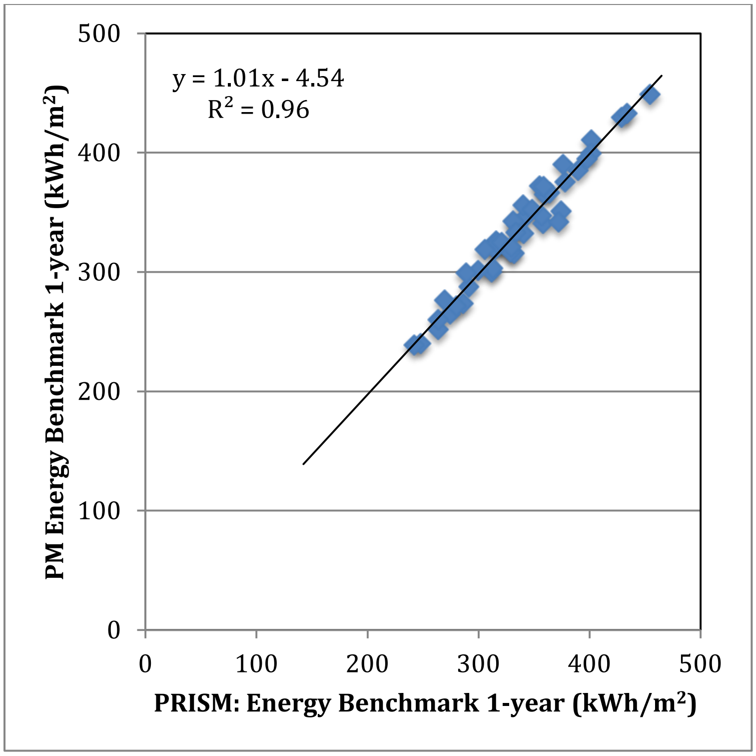

Figure 4-34: Benchmarking result using 1-year bill comparison: PM vs. PRISM

4.10 Retrofit Assessment

In the PRISM analysis, significant energy consumption changes were identified in 27 gas-heated MURBs. Some of the MURBs had multiple energy consumption changes in the billing periods of up to five years. Seven MURBs had two energy consumption changes and one MURB had three changes. Among them, three MURBs were not able to perform the savings assessment due to missing monthly bills or unrealistic readings. Therefore, 24 MURBs were assessed for energy savings.

Because the retrofit information was not provided, it is unknown if the changes were due to implementation of energy conservation measures or random factors. In this thesis, energy consumption changes are assumed to be due to retrofit.

The retrofit is within the -45.6–103.7 kWh/m^2 range. The negative energy saving results indicates the corresponding MURB had an increase in the energy consumption. Nine MURBs showed an increase in the overall energy consumption. The total energy saving assessed by PRISM is displayed in Table 4-9.

The energy consumption pattern changes were provided to the building owners and information on the changes in the building was requested. Only one MURB, building “Bldg1”, confirmed their retrofit during the time of study. The building “Bldg1” upgraded the lighting system in the underground parking in early 2010. The energy consumption saving was identified by PRISM around May 2010. The observation on the utility bills matches the retrofit in the building. The estimated electricity saving is 5.9 kWh/m^2, which is 8% of total electricity. During the same time period, the gas consumption showed 15% drop. The gas saving is majorly from the heating-related consumption. The explanation for gas saving needs further investigation, because the author was not provided the opportunity to study if other retrofits were implemented.

The highest energy saving is in building “4790’. This building had electricity and gas saving of 18.4kWh/m^2 and 85.3 kWh/m^2, respectively, which in total 103.7 kWh/m^2. The percentage savings of this MURB is 24%. Building “4790” was built in 1972. After the retrofit, this building has the second highest energy efficiency in buildings built before 1975 and is the seventh most efficient in all buildings tested. It’s highly recommended that future study investigate the type of retrofits that were applied to this building. The success showed by the substantial improvement in this building can be a good example for peer MURBs.

Table 4-9: PRISM assessed energy saving using multiple year bills

Building ID	Electricity Saving (kWh/m^2)	Gas Saving (kWh/m^2)	Total Energy Saving (kWh/m^2)	Total energy Saving Percentage
3798	-4.8	-40.9	-45.6	-14%
5528	4.2	-29.0	-24.8	-7%
4359-Retrofit 1	6.5	-30.7	-24.2	-7%
3496-Retrofit 2	3.8	-19.4	-15.6	-4%
4741	11.0	-26.2	-15.1	-5%
3624	10.6	-24.2	-13.6	-4%
5645	9.9	-23.3	-13.4	-5%
4077	-6.0	-3.7	-9.7	-3%
4018	10.8	-5.8	5.0	1%
4359-Retrofit 2	9.4	3.6	13.1	4%
3477-Retrofit 2	1.2	17.2	18.4	4%
5964	-3.6	25.6	21.9	8%
4115	14.2	8.9	23.1	7%
5634	-8.9	35.5	26.6	9%
5521-Retrofit 2	0.8	27.9	28.6	8%
3242	12.0	21.8	33.8	9%
3477-Retrofit 1	2.5	32.8	35.3	9%
3983	-2.4	37.8	35.4	10%
4359-Retrofit 3	-5.8	42.9	37.2	9%
Bldg1	5.9	32.2	38.1	13%
4358-Retrofit 1	8.4	30.2	38.6	10%
3497-Retrofit 2	8.3	31.5	39.8	10%
5521-Retrofit 1	-0.5	40.5	40.0	12%
3496-Retrofit 1	2.9	39.2	42.1	11%
4078	4.8	49.8	54.7	14%
3497-Retrofit 1	5.3	55.6	60.9	16%
4079	4.5	59.7	64.2	18%
3145-Retrofit 1	1.8	62.7	64.5	15%
4358-Retrofit 2	-0.5	74.9	74.4	17%
3145-Retrofit 2	8.2	67.4	75.6	14%
4053	-2.1	94.1	92.0	24%
4790	18.4	85.3	103.7	24%

4.10.1 Energy Saving Assessment by End-use

The gas consumption savings determine the total energy savings as displayed in Figure 4-35. The electricity savings compared with gas consumption savings is a very small portion, which in the majority of the MURBs is less than 10%. In the following MURBs, the electricity contributed to a higher percentage of the total savings than gas savings: building “3242” at 35.4%, “4115” at 61.5%, “4358” at 20.2%, “4790” at 17.7%, and “4359” Retrofit 2 at 72.3%. It can be inferred that to target overall energy consumption savings, the building owners should focus on the gas consumption saving strategies.

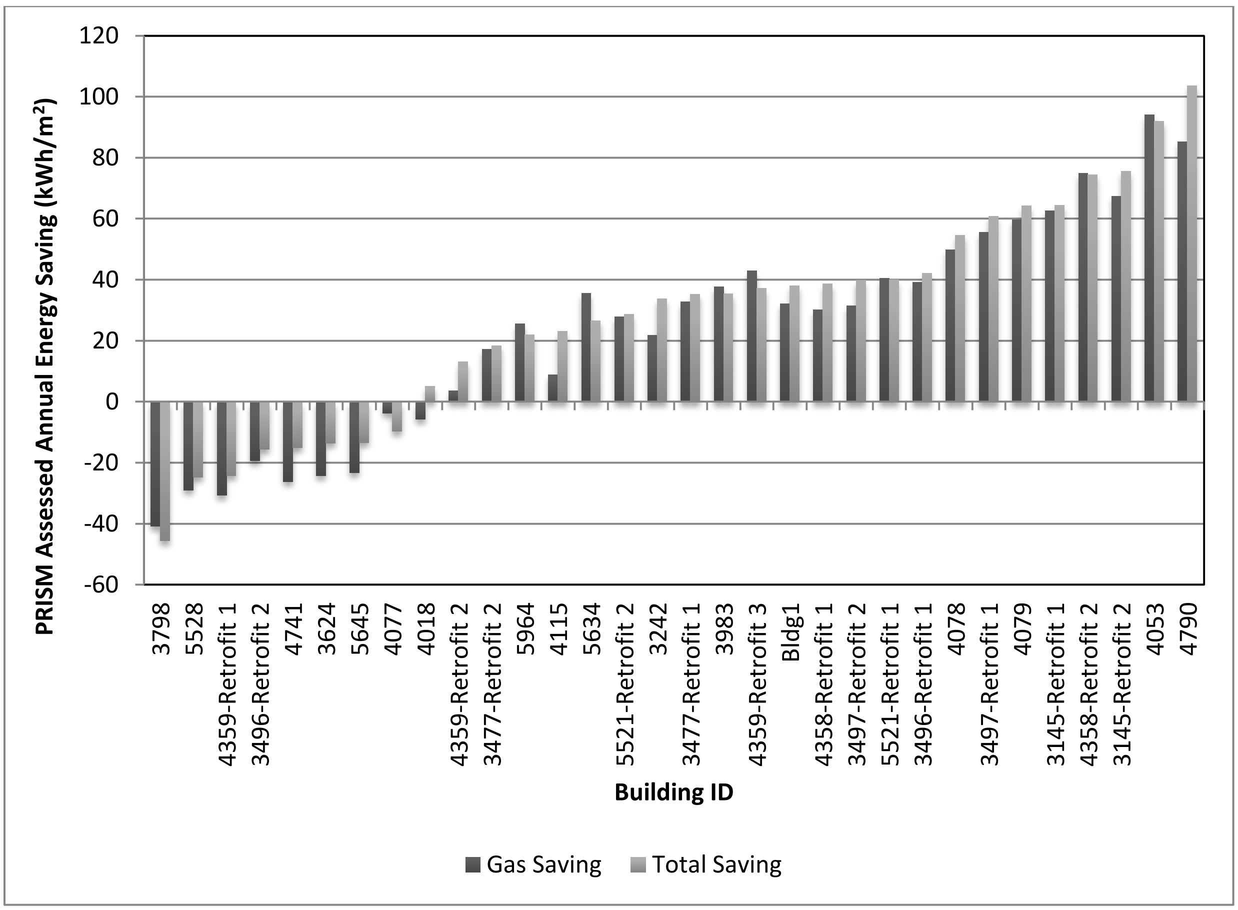

Figure 4-35: PRISM assessed energy saving: gas saving vs. total saving

The energy consumption of each end-use before and after retrofit was calculated using PRISM. The result is illustrated in Figure 4-36. It is found that 23 retrofits in the MURBs had a decrease of heating-related gas consumption, accompanied with increase in base gas consumption.

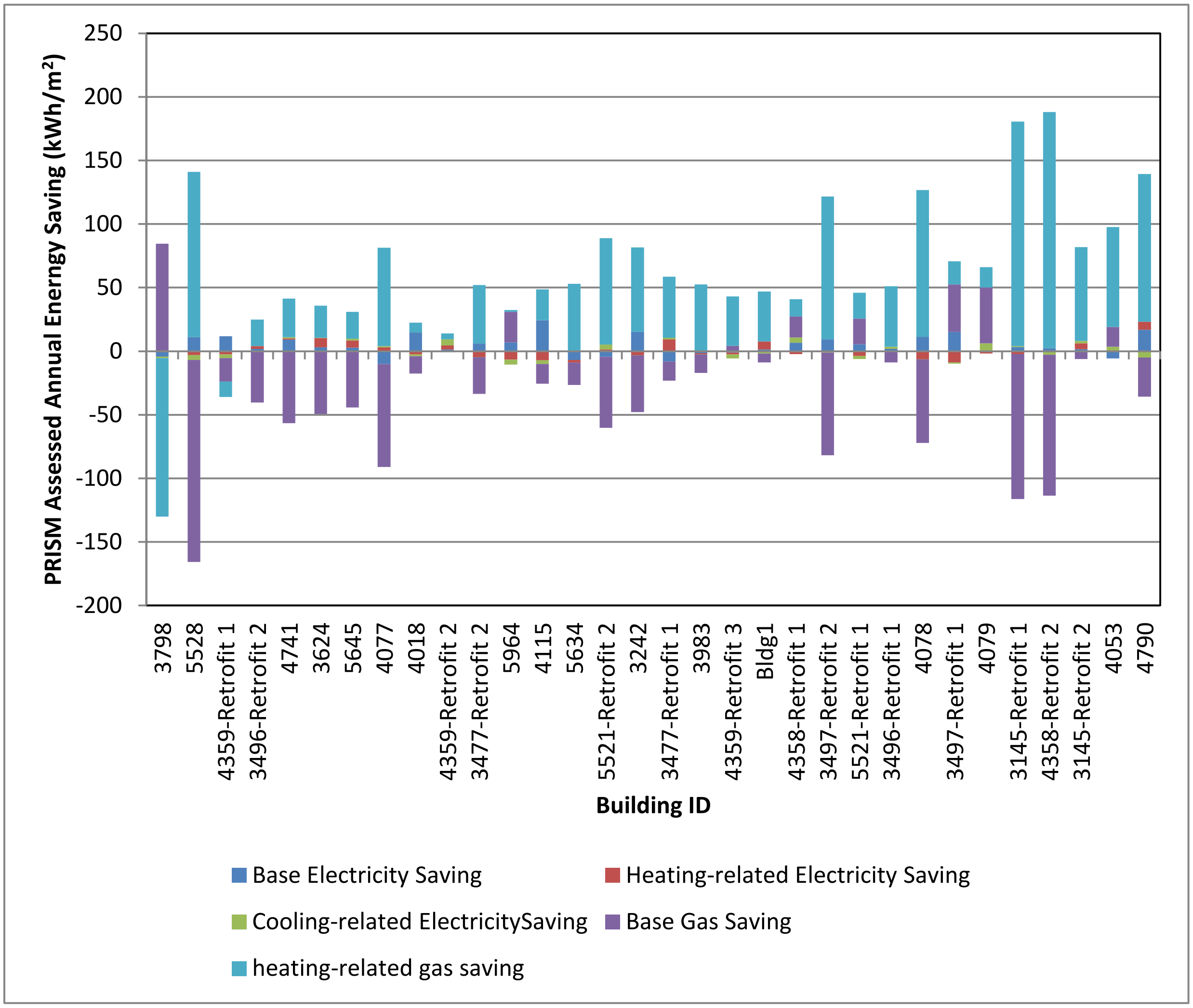

Figure 4-36: Energy saving by end-use, in the order of lowest to highest overall energy saving

4.10.2 Energy Signature Changes

The energy signature is changed by retrofit for both electricity and gas consumptions. The heating slope and cooling slope are given by PRISM in the unit of kWh/˚F-day for electricity and m^3/˚F-day for gas. In order to compare the energy signature s of buildings with different gross floor are, the heating slope and cooling slope were divided by the gross floor area. The units were converted to kWh/˚C-day/m^2.

Table 4-10: Energy signature change of the 23 retrofitted buildings

Energy Type	**Electricity**				**Gas**	
Building Group	**Heating Reference Temperature (˚C)**	**Heating slope (kWh/˚C-day/m^2)**	**Cooling Reference Temperature (˚C)**	**Cooling Slope (kWh/˚C-day/m^2)**	**Heating Reference Temperature (˚C)**	**heating slope (kWh/˚C-day/m^2)**
Building with increased energy use	-2.5	0.0031	0.3	0.0014	-4.6	0.0057
Building with net energy saving	0.4	-0.0011	-0.7	-0.057	-2.1	-0.011

For the 23 buildings that showed decrease in energy consumption, on an average, the reference temperature of gas heating consumption decreased 2.1°C with a decrease of heating slope of 0.011 kWh/°C-day/m^2. This indicates that the MURBs require gas heating at a lower outdoor temperature after retrofit meanwhile the heating required per degree drop is decreased. This may be the effect of better building equipment. The lower the reference temperature is, the lower the HDD for the given weather. The lowered reference temperature is an indication of a more efficient building.

The heating reference temperature for electricity consumption increased by 0.4°C and the heating slope increased 0.0011 kWh/°C-day/m^2. The increased heating demand per degree drop can be a result of increased demand for heating-related electricity consumption due to the reduced gas heating consumption.

For the nine MURBs which showed increased energy consumption, the reference temperature for gas heating decreased by 4.6°C on average. The heating slope increased by

0.0057 kWh/°C-day/m^2. Those nine MURBs required gas heating at a lower outdoor temperature, but for a given outdoor temperature drop, the demand for heating increased. For electricity consumption, the mean cooling reference temperature dropped 2.5°C and the mean heating slope increased 0.0031 kWh/°C-day. Those change lead to the net increase in energy consumption.

4.10.3 Energy Saving Assessment: SRWN vs. PRISM

The energy saving assessment using SRWN method is compared with PRISM results. The results are listed in Appendix E. Statistically; the results from two methods are relatively well correlated with an R^2 at 0.80 as displayed in Figure 4-37. The slope of the plot in Figure 4-37 is 1.00, with an intercept of 0.04. In the studied buildings, on an average, SRWN tends to overestimate the overall savings by 23.3%.

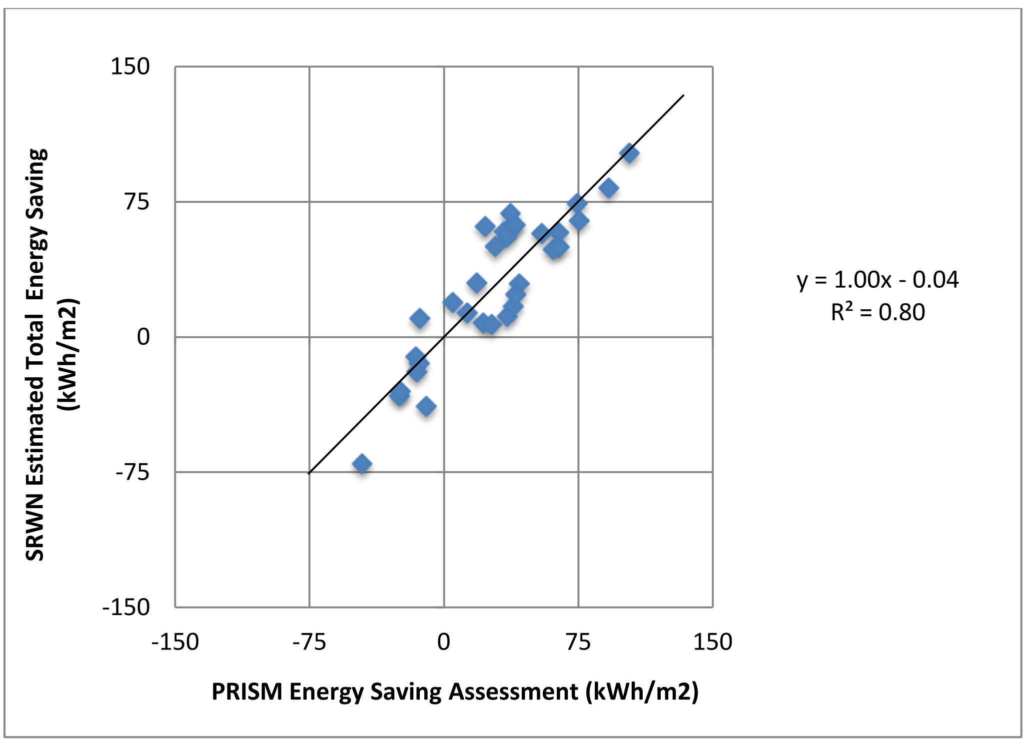

Figure 4-37: Total energy saving assessment: SRWN vs. PRISM

However, on the individual basis, the SRWN calculated energy saving deviated from PRISM results. The electricity saving calculation is less correlative between SRWN and PRISM. The electricity saving range is from -8.9-18.4 kWh/m^2. The linear regression of saving calculation by SRWN and PRISM is illustrated in Figure 4-38. The correlation gives an R^2 of 0.48, which indicates that only 48% of the sample follows the relation. The slope is 1.37 with an x-intercept of 3.02. The SRWN method gives a range of -15.2-22.1 kWh/m electricity saving. In the studied buildings, on an average, SRWN tends to overestimate the electricity savings by 72.8%.

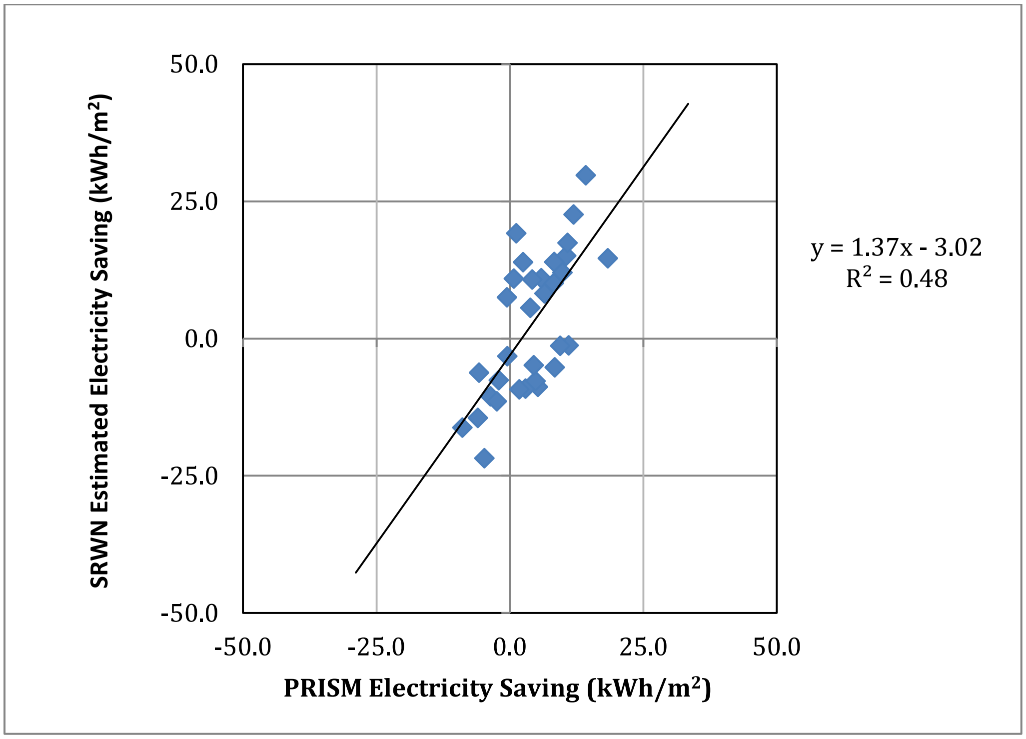

Figure 4-38: Electricity saving assessment: SRWN vs. PRISM

Gas saving gives closer results between the two methods, which is shown in Figure 4-39. The R^2 of the plots is 0.91, showing a high correlation between the two methods. In the studied buildings, on an average, SRWN tends to overestimate gas savings by 33.3%.

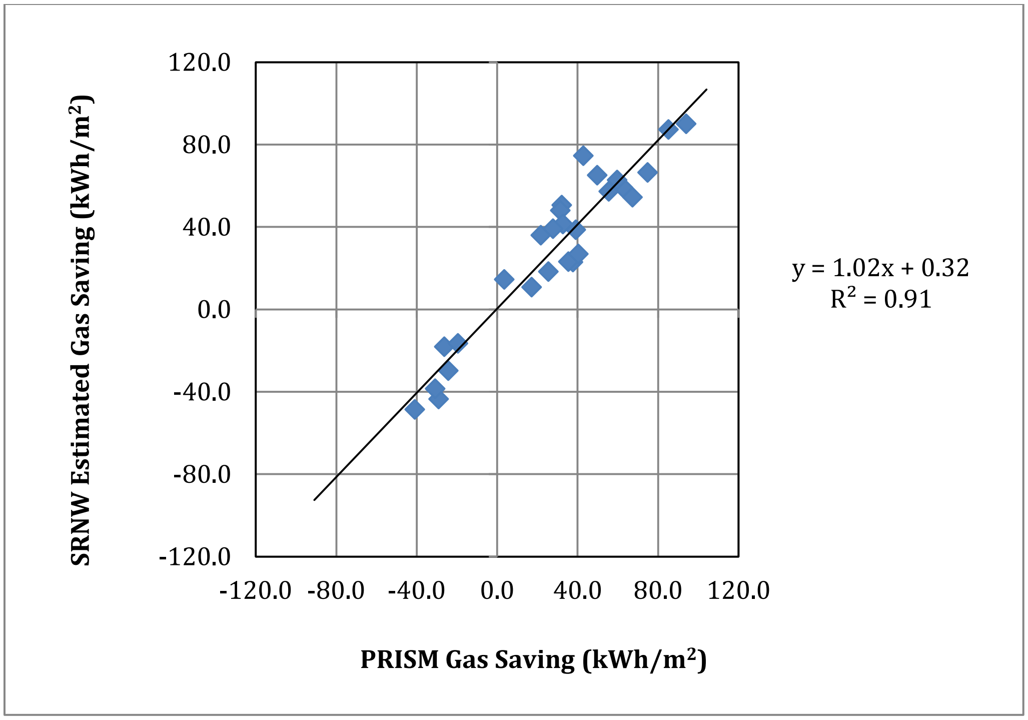

Figure 4-39: Gas saving assessment: SRWN vs. PRISM

The energy saving assessment was based on monthly bills. However, for building "3798", "4115", "4741", "5634", and "5521", at least one bi-monthly reading was used in each building due to the original received records. The comparison of the results using these two different methods is shown in Table 4-10.

Table 4-11: Comparison of PRISM estimated NAC based on multiple-year and 1-year utility bills

Building ID	Retrofit Type	Estimated Retrofit Time	Overall Energy Saving (kWh/m^2)		
			PRISM	SRWN	PM
3798	Gas	11/1/2010	-45.6	-70.4	-17.5
4115	Electricity	11/1/2010	23.1	61.3	28.8
4741	Electricity & Gas	12/1/2009	-15.1	-19.4	19.1
5521-Retro2	Gas	3/1/2008	28.6	50.1	17.0
5634	Electricity & Gas	3/1/2011	26.6	7.0	32.9

The energy saving assessments for these five MURBs are not consistent when using different methods. This suggests that using bi-monthly bills in SRWN and PM may deteriorate the energy saving calculation.

4.10.4 Energy Saving Assessment: PM vs. PRISM

The energy saving assessed by PM and PRISM based on 1-year pre-retrofit and 1-year post-retrofit utility bills is listed in Appendix F. The relation between the PM and PRISM energy saving calculations is plotted in Figure 4-40. The R^2 at 0.67 indicates that there is a moderate correlation between results from the two methods. In the studied buildings, compared with PRISM, PM underestimates the saving results by up to 21.5%.

The major difference between PM and PRISM is that the PM calendarized the monthly consumption before the weather normalization, and use HDD and CDD to adjust the monthly reading to the long-term weather. The deviation is likely from the assumptions that the daily consumptions in each reading remain constant. This deviation is exaggerated by using bi-monthly readings.

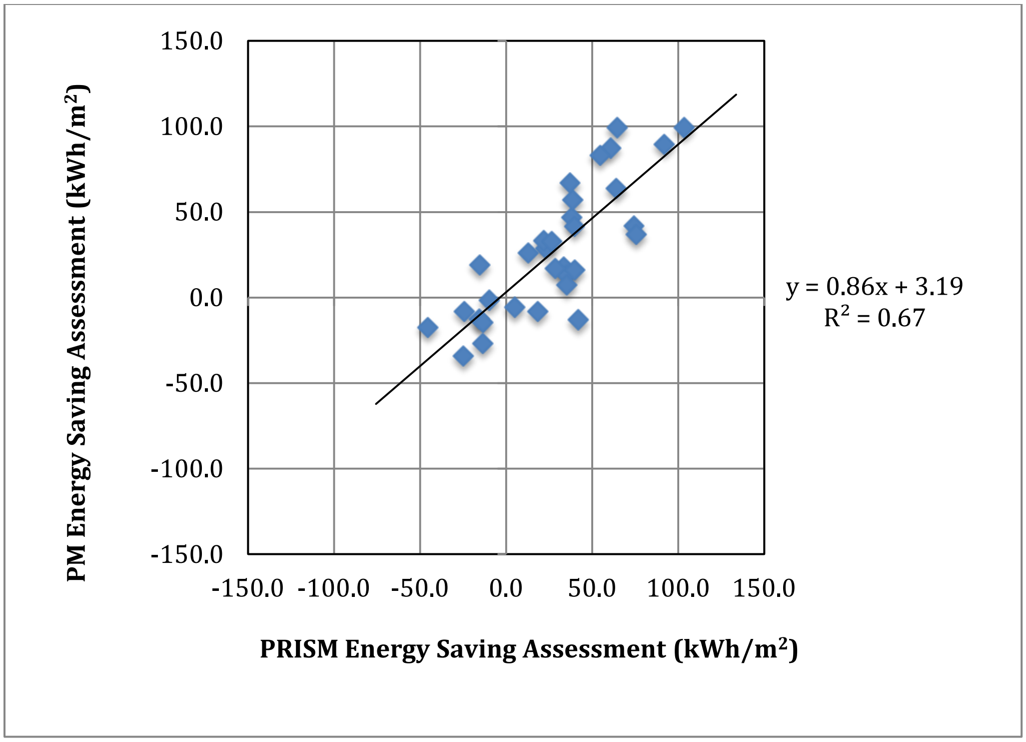

Figure 4-40: Total energy saving assessment: PM vs. PRISM

In the studied buildings, the electricity saving assessment by PM can be underestimated by up to a 121%. However, the electricity saving is a relatively small portion of the total energy saving, the deviation from the electricity saving assessment does not substantially affect the total saving calculation. The correlation between the two methods has an R^2 at 0.69 with an x-intercept of 0.17 and slope of 0.92. In the studied buildings, on an average, the PM tends to underestimate the electricity saving by 10.5%, comparing with PRISM.

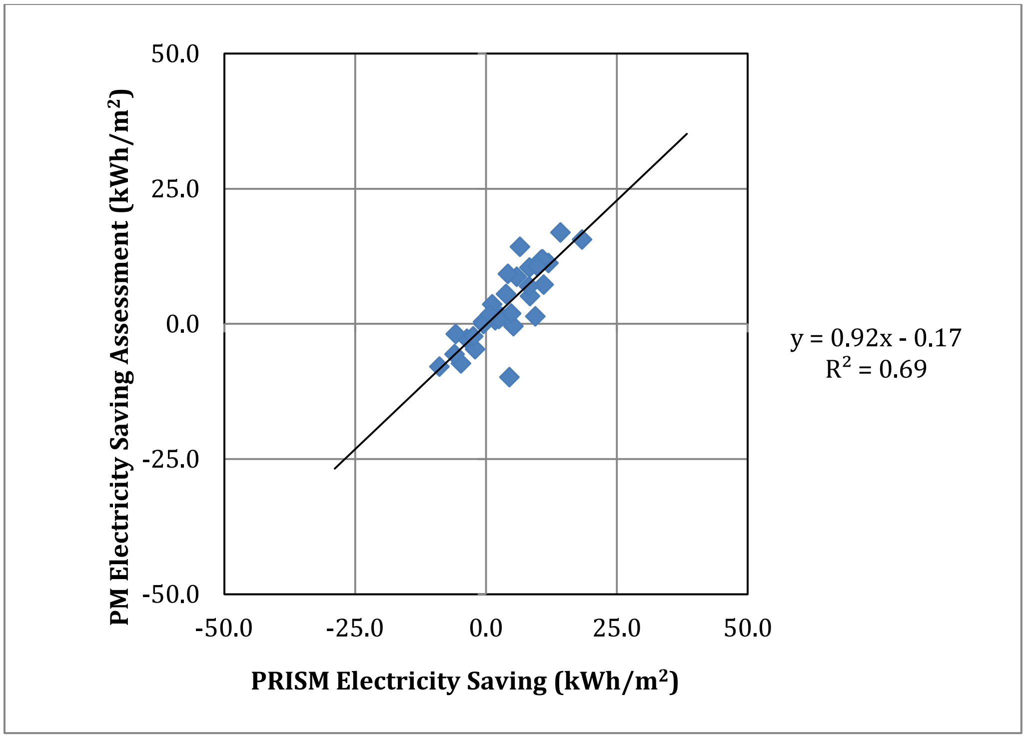

Figure 4-41: Electricity saving assessment: PM vs. PRISM

The relation of gas saving assessment using PM and PRISM is illustrated in Figure 4-42. The linear regression between the results from two methods has an R^2 at 0.65, slope at 0.89, and an intercept of 2.15. In the studied buildings, on an average, PM underestimated the gas saving result by 4.8%.

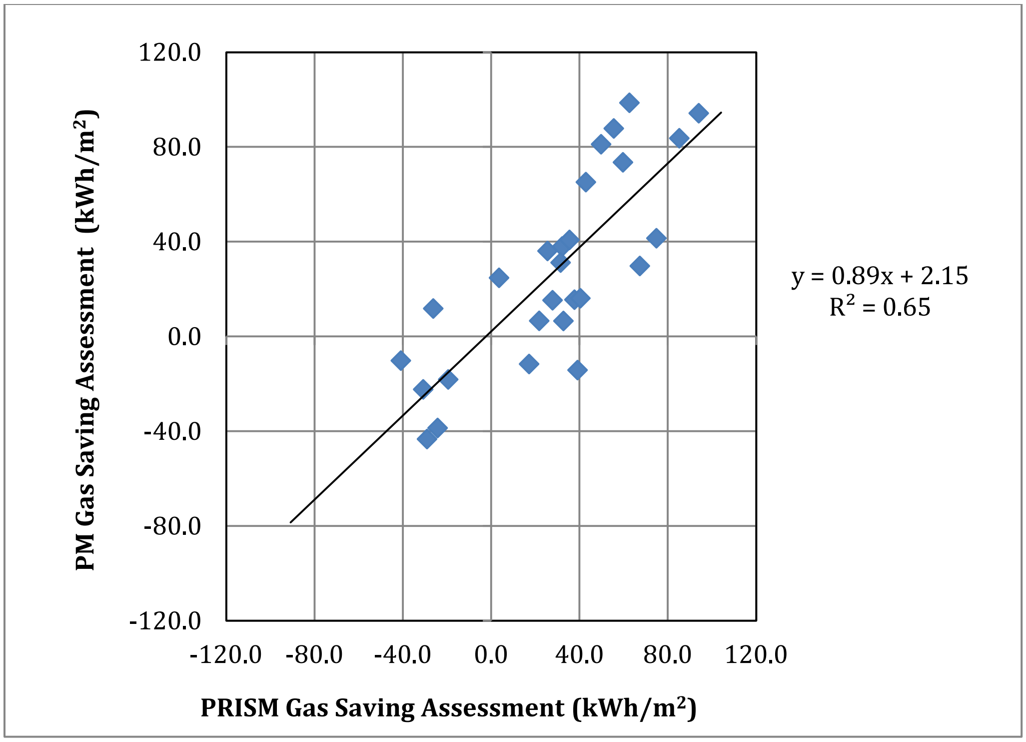

Figure 4-42: Gas saving assessment: PM vs. PRISM

4.11 GHG Emissions

The GHG emissions of studied MURBs are estimated using Environment Canada carbon emission index. The overall greenhouse gas intensity for electricity in Ontario is 170 g CO^2 eq/kWh in 2008 (Environment Canada, 2010). The emission factor for gas in residential sector use is 1879 g CO^2 eq/m^3 (Environment Canada, 2011a).

The GHG emissions for the 45 gas-heated MURBs are within the range of 42.9 and 81.5 kg CO^2 eq/m^2. The mean of GHG emission is 58.6 kg CO^2 eq/m^2. The greatest portion of GHG emissions comes from heating gas consumption, ranging from 34.8% to 65.9%. On an average, 51.5% of GHG emissions were contributed by heating gas consumption.

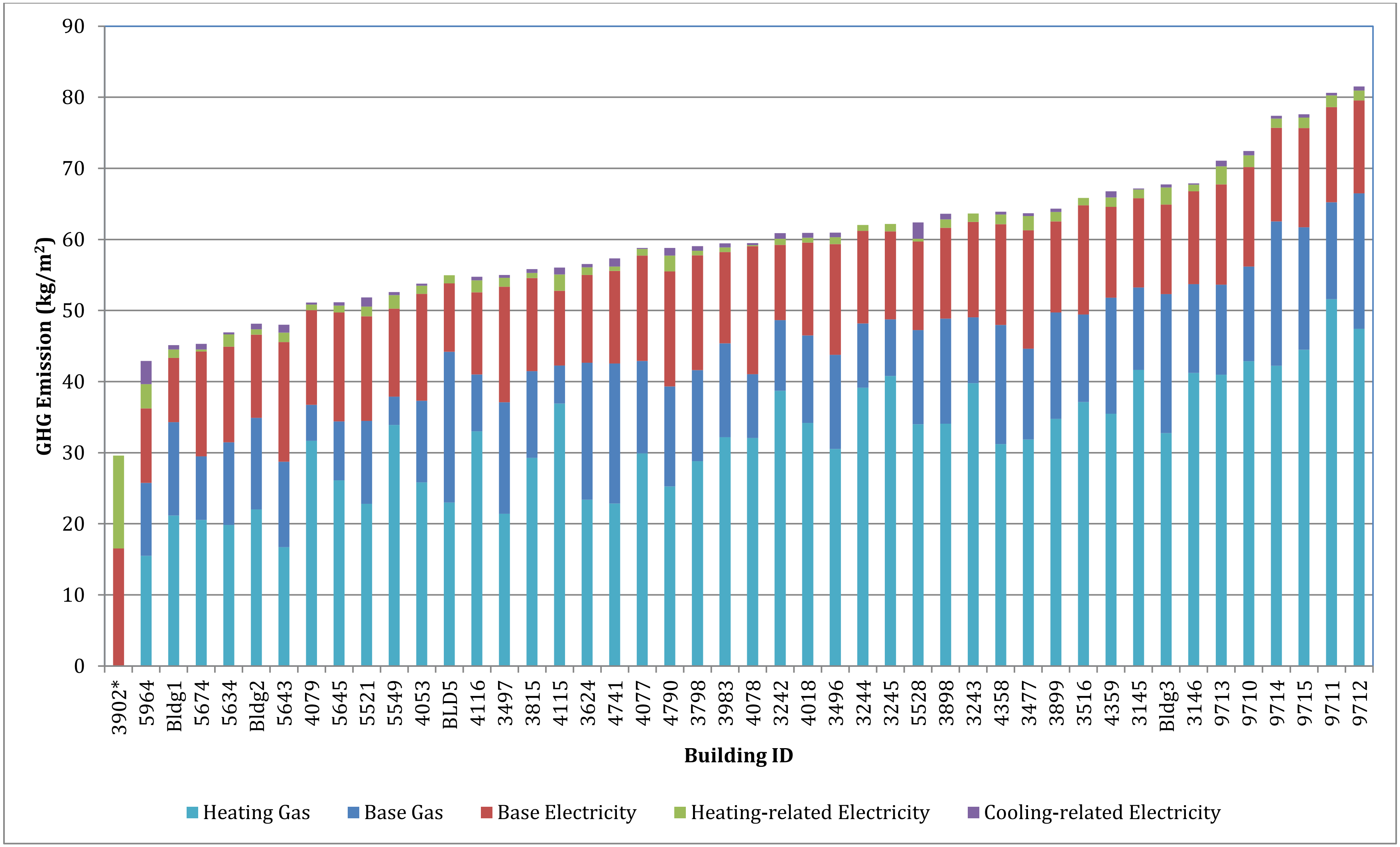

Figure 4-43: GHG emission by end-use

5 Conclusion and Recommendations

5.1 Conclusion

This research evaluated energy consumption of 45 gas-heated and 1 electric-heated high-rise MURBs, which were built in 1962-1984 and located in Greater Toronto Area. The developed database is the best of its kind in Canada. All buildings were successfully analyzed by PRISM, indicating that both electricity and gas consumption in the studied MURBs is linearly related to the outdoor temperature. In the high-rise MURBs, management offices operate the major energy use for space heating, ventilation and common area lighting; thus, at an aggregated level, the influence of randomness of tenants' behaviour is minimized.

Annual energy consumptions were normalized to 30-year Toronto weather from January 1, 1981 to December 31, 2010 using PRISM. The HDD and CDD based on 18°C are 3879 and 305 respectively. The normalized annual energy consumption of the gas-heated MURBs is within the range of 242–453 kWh/m^2, with a mean of 336 kWh/m^2 and standard deviation of 51 kWh/m^2.

The only electric-heated MURB has a higher energy efficiency compared with other MURBs. The electric-heated building consumed 174 kWh/m^2 energy per year. Due to limited number of sample, the energy efficiency of electric-heated buildings needs further investigation.

The vintage of the MURB plays an important role in the MURB overall energy consumption. The implementation of first building code in Ontario in 1975 had a positive influence on the building energy efficiency. For the 45 gas-heated MURBs, buildings built after 1975 on an average consumed 280 kWh/m^2 while buildings built before 1975 consumed 348 kWh/m^2. The newer MURBs used 19% less energy while the gross floor area is 12% larger.

The energy consumption changes were mostly from decreased gas heating consumption and increased cooling-related electricity consumption. On an average, MURBs built after 1975 consumed 33% less heating gas and 117% more cooling-related electricity. Overall, the newer MURBs showed decrease in energy consumption.

The volume of the building, number of major appliances and occupancy of the MURBs were found to have little direct influence on the overall energy consumption.

Energy saving assessments showed that the 32 retrofits in 24 MURBs had energy consumption changes ranged from 45.6 increase to 103.7 kWh/m^2 decrease. Among them, nine buildings showed increase in energy consumption. More than 90% of the energy consumption changes were from gas consumption changes.

It is found that 23 retrofits in the MURBs that had a decrease of heating-related gas consumption, accompanied with increase in base gas consumption. The MURBs that had net energy saving required gas heating at a lower outdoor temperature after retrofit and require less gas heating per degree drop in temperature, meanwhile the electricity consumption increased per degree drop in temperature. This indicated that with the decreased gas consumption for space heating, occupants tend to use more heating-related electricity to maintain comfortable living environment.

All the MURBs were benchmarked using SRWN method and PM. Both methods showed good consistence with PRISM results. On an average, SRWN benchmarking results deviated 3.7% from PRSIM results, while PM 0.5%. If rough estimation of NAC is needed, SRWN can be a cost-effective and user-friendly tool for the purpose. For PM analysis, the errors brought by calendarized monthly consumption are negligible. However, the use of SRWN and PM in energy saving assessment showed greater deviations from PRISM results. Energy saving calculated by SRWN method tends to overestimate the energy saving by 23% while PM underestimates by 21%.

The GHG emission of the 45 gas-heated MURBs is within the range of 42.9 and 81.5 kg CO_2 eq/m^2. The mean GHG emission is 66.7 5 kg CO_2 eq/m^2. Based on 2011 Toronto utility rates, the cost of energy was from 43.7 to 92.6 Canadian dollars per square meters, with a mean value of 66.7.

Some of the buildings had substantial energy savings in the recent year. It can be inferred that with proper energy saving measure, those aging buildings are likely to reduce energy consumption, as well as GHG emissions and cost. There is great opportunity in reducing negative impact on the environment in those older MURBs.

5.2 Future Work

This thesis project is a preliminary research on the energy efficiency of high-rise MURBs as a part of Toronto Tower Renewal project. Many difficulties occurred during data collection and acquisition of feedback. The data for more buildings and retrofit information was still pending at the end of this thesis research. The benchmarking development will continue and the complete database will contain information on approximately 160 high-rise MURBs.

Although the energy consumption of studied MURBs is mostly influenced by outdoors temperature, it is recommended to evaluate various factors that may impact on energy efficiency in the MURBs. Table 6-1 lists the factors to be examined, which include building characteristics, occupancy information, surrounding environment, and weather conditions. This extended research can be achieved by development of multi-regression and/or ANN models.

Table 6-1: Factors that may influence energy consumption in MURBs

Category	Building Characteristics (Catalina et al., 2008)	Occupancy Information (Rey et al., 2007)	Surrounding Environment (Lewis & Laverne, 2003)	Climate (Catalina et al., 2008)
Factors	Orientation Building morphology Building envelope HVAC Lighting Window to floor area ratio Amenities	Occupancy Type Demographic Number of occupant	Vegetation	Humidity Solar radiation Wind

The retrofit information would be valuable to evaluate the actual effectiveness of various energy saving measures. Once the retrofit information is provided, an ANN model can be developed to predict the potential energy savings of MURBs of similar characteristics. Unlike engineering models, ANN models based on empirical data can account for rebound effects in MURBs.

Appendix A

Benchmarking Survey

Minimum Required Data

1. Building Specification

    - Age of the building
    - Number of floors
    - Total floor area
    - Number of suites
    - Heating system fuel type (e.g. electricity, gas, etc)
    - Cooling system if applicable (e.g. central AC, portable AC, window AC)
    - Type of major retrofit within the utility bills period, and implementation date or month

        - ❖ Mechanical upgrade
        - ❖ Appliances
        - ❖ Lightings
        - ❖ Toilets
        - ❖ Building envelope
        - ❖ Others

2. Utility bills (3-year monthly data)

    - Electricity
    - Natural gas
    - Water

- Waste (2 years data)

3. Green power (if applicable)

    - Type of green power and quantity produced

4. Occupancy

    - Number of vacant suites or vacancy rate in any available format (e.g. by month, by year, etc.)
    - Average total number of occupants

Desirable Data

1. Building type (e.g. rental apartment, condominium, social housing, etc.)
2. Building orientation
3. Type of light bulbs (e.g. incandescent, compact fluorescent, T5, T8, T12, etc.)
4. Indicate shared appliances (e.g. washers, dryers, etc.)
5. Window glazing layers (e.g. single, double, storm, etc.)
6. Indicate if water is used the following purpose
    - Swimming pools
    - Landscape irrigation
7. HVAC system

Appendix B

C++ Program for HDD_a Calculation

```
(#include "test 1.h"


using std::cout;
using std::cin;
using std::endl;

int main ()
{
      int S;
      cout << "enter the stating date";
      cin >> S;
      int E;
      cout << "enter the ending data";
      cin >> E;
      long double billy [] = {A*}s;

      long double HDD = 0;
      int i;

      for (i=S; i <= E; i++ )
      {
            HDD += billy[i];
      }
            cout << "HDD is " << HDD;
            cout << " \n" ;
      system("pause");
      return 0;
}
```

A*: This bracket contains daily HDD from January 1, 1900 to June 30, 2012, based on 18˚C, and were separated using ",". The use of the dates from January 1, 1900 to December 31, 1980 is to be compatible with the input date format. Those HDDs were not used in the research and were marked as "0". Historical daily HDDs from January 1, 1981 to July 31, 2012, were retrieved from National Climate Data and Information Archive. Due to large amount of data, this thesis doesn't include the daily HDDs in the appendix.

The input starting date and ending date in this C++ program uses MS Excel dates storage method. After typing a date in the MS Excel cell, change the cell format to "text". The date is converted to a number. In this date storage method, January 1, 1900 is used as the base date "1". The stored number means the number of days elapsed starting from January 1, 1900. For example, for a billing period from March 1, 2011 to February 29, 2012, the input to this C++ program is as follows:

entering the starting date: 40603

entering the ending date: 40968

The output will be:

HDD is 3360.8

Appendix C

Sample Building Performance Assessment Report

Since the benchmarking project was ongoing, the number of the buildings increased after the completion of the data analysis for this thesis. Therefore, in this sample report, 52 buildings were benchmarked, including the 45 buildings used for further analysis in this thesis.

The water and solid waste benchmarking were completed by the fellow project partner Ms. Mahssa Ghajarkhosravi.

BUILDING PERFORMANCE ASSESSMENT

The Building Performance Assessment provides analysis using benchmarked utility consumption of 52 buildings located in City of Toronto. All buildings meet the characteristics of the City's Tower Renewal program: the buildings are 8 stories or more and were built from 1945 to 1984.

Building Characteristics:

Building ID:	4079	Year Built:	1972		
Gross Floor Area (m^2):	32420	# of Units:	421	# of Stories:	18

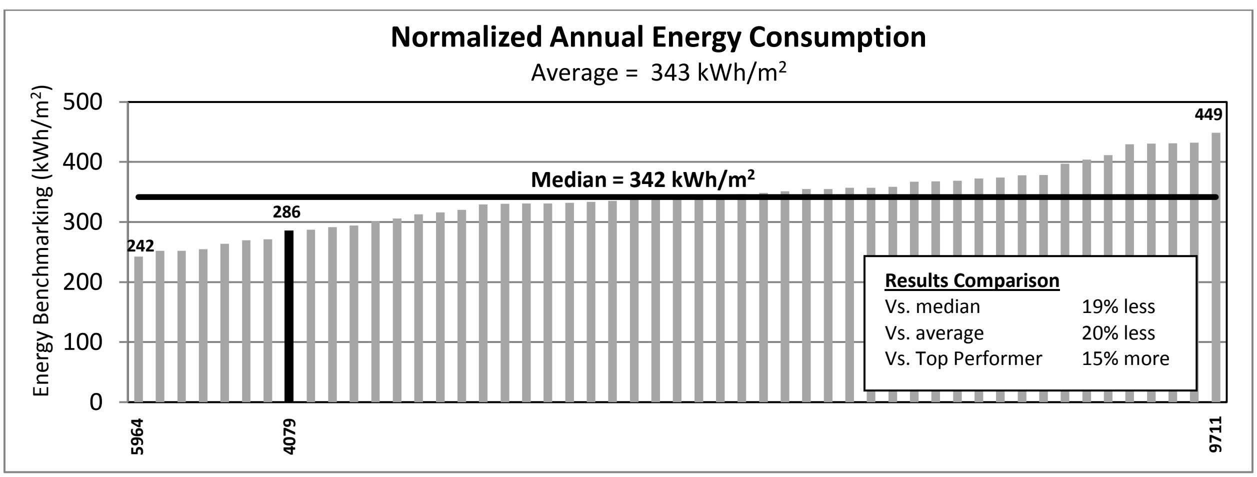

Figure 1: Annual energy consumption benchmarks of 52 residential buildings

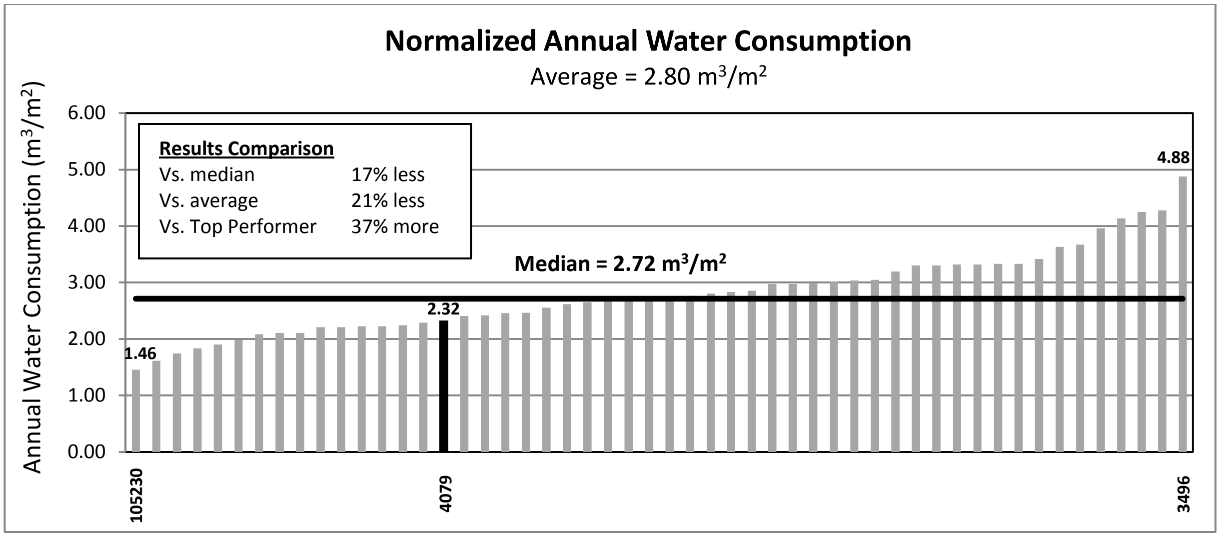

Figure 2: Annual water consumption benchmarks of 52 residential buildings

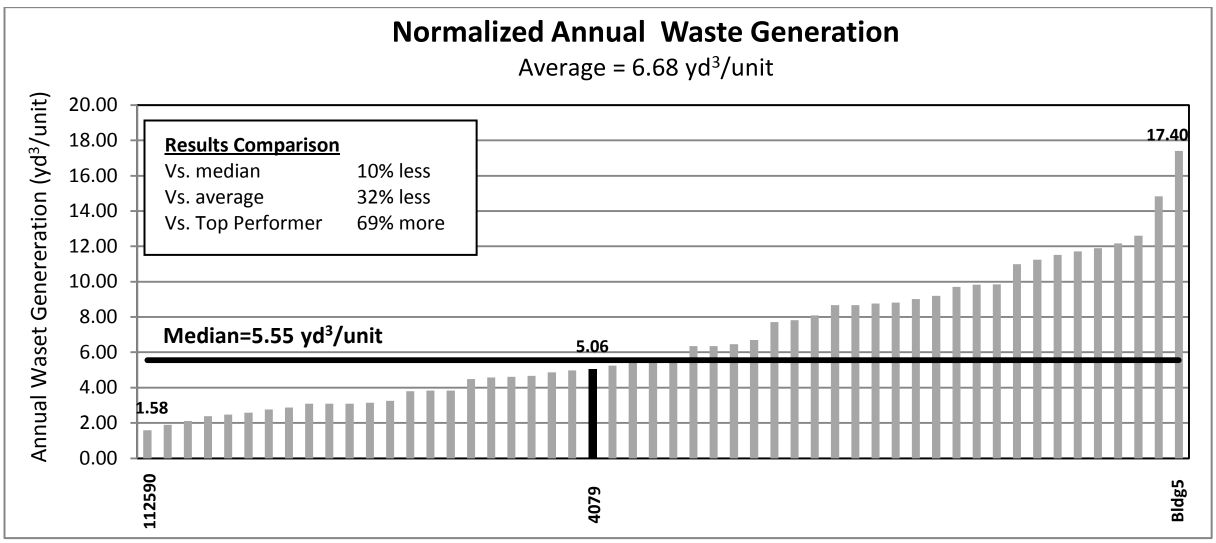

Figure 3: Annual waste generation benchmarks of 52 GTA residential buildings

PERFORMANCE ANALYSIS

ENERGY[4]		Building ID	Saving Potential	
		4079[5]	(%)	($)[6]
ELECTRICITY (kWh/m²)	Annual Base Consumption	**78.2** (53.2)	32%	$77808
	Annual Heating-related Consumption	**4.6** (0.2)	96%	$13694
	Annual Cooling-related Consumption	**1.8** (0.9)	50%	$2801
	Annual Electricity Consumption	**84.6** (63.7)	28%	$94304
GAS (kWh/m²)	Annual Base Consumption	**28** (21.9)	21%	$6960
	Annual Heating-related Consumption	**174** (85.0)	51%	$104873
	Annual Gas Consumption	**202** (141)	30%	$111833
Annual Energy Consumption (kWh/m^2)		286	15%	$206137

WATER	Building ID	Saving Potential	
	4079	(%)	($)
Annual Water Consumption (m^3/m^2)	2.32	37%	$53275

WASTE[7]	Building ID	Saving Potential	
	4079	(%)	($)
Annual Waste Generated (yd^3/unit)	5.06	69%	$21019

[4] Energy benchmarks provided in this report are weather normalized.
[5] In this analysis, the Top Performer has been defined as the building that shows the lowest consumption in each sub-category or category. A building can be the Top Performer overall while other buildings are the Top Performer in each sub-category. The number in parentheses is the Top Performer consumption amount for that sub-category.
[6] Saving potential estimates are based on 2011 invoice payments.
[7] This waste benchmark is based on the most recent year 2011 bill.

Appendix D

Normalized Annual Energy Consumption by PRISM, Simple Ratio Weather Normalization, and ENERGY STAR® Portfolio Management

Table D-1: Energy Benchmarking by PRISM, SRWN and PM

Building ID	PRISM Multiple Year Bills (kWh/m^2)	Benchmarking Comparison (1-year Utility Bill)		
		PRISM (kWh/m^2)	Simple Ratio Weather Normalization (kWh/m^2)	ENERGY STAR® Portfolio Management (kWh/m^2)
3145	374	374	394	351
3146	378	378	387	375
3242	339	340	339	344
3243	355	335	359	340
3244	346	360	380	365
3245	347	364	389	366
3477	357	358	385	341
3496	341	341	376	332
3497	309	315	311	319
3516	368	402	398	411
3624	316	316	320	326
3798	331	331	336	343
3815	312	317	320	324
3898	355	355	362	372
3899	359	359	361	372
3983	332	332	354	316
4018	340	340	345	356
4053	302	312	337	300
4077	329	329	353	317
4078	334	334	330	333
4079	286	286	305	274
4116	306	300	303	301
4358	357	357	349	347
4359	372	372	390	342
4741	321	321	321	325
4790	331	330	361	321
5521	291	291	316	288

5528	348	349	347	352
5549	294	289	296	299
5634	264	264	287	252
5643	271	275	300	265
5645	287	280	305	271
5674	255	248	271	240
5964	242	242	254	239
9710	404	401	412	400
9711	449	455	463	449
9712	453	429	443	430
9713	397	390	395	385
9714	431	398	404	395
9715	432	434	445	433
Bldg1	252	264	259	260
Bldg2	270	270	265	276
Bldg3	378	376	375	390
Bldg5	306	306	356	319

Appendix E

The f-test and t-test results for end-use energy consumption

Table E-1: F-test and T-test results for electricity consumption

Group	Calculation	Base Electricity Consumption	Heating Electricity Consumption	Cooling Electricity Consumption	Overall Electricity Consumption
1962-1964 vs. 1968-1973	f - calculated	21.27*	3.61	1.85	6.61*
	f - 0.05 (28/5)	4.50	4.50	4.50	4.50
	s	10.33	3.22	2.50	10.18
	t - calculated	0.797*	0.086	1.521	1.210*
	t - 0.05	2.035	2.035	2.035	2.035
	t - 0.01	2.733	2.733	2.733	2.733
1968-1973 vs. 1978-1979	f - calculated	0.55	0.70	2.02	0.34
	f - 0.05 (28/4)	5.75	5.75	5.75	5.75
	s	11.73	3.51	2.51	12.14
	t - calculated	1.189	0.364	1.285	0.779
	t - 0.05	2.037	2.037	2.037	2.037
	t - 0.01	2.739	2.739	2.739	2.739
1978-1979 vs. 1982-1984	f - calculated	0.89	0.27	0.06	4.71
	f - 0.05 (4/3)	9.12	9.12	9.12	9.12
	s	15.51	6.06	5.05	15.16
	t - calculated	1.060	0.244	1.039	1.528
	t - 0.05	2.365	2.365	2.365	2.365
	t - 0.01	3.499	3.499	3.499	3.499
before 1975 vs. After 1975	f - calculated	0.43	0.31	0.25	0.39
	f - 0.05 (34/8)	3.06	3.06	3.06	3.06
	s	11.49	3.79	3.19	11.66
	t - calculated	0.285	0.763	2.869	0.751
	t - 0.05	2.018	2.018	2.018	2.018
	t - 0.01	2.698	2.698	2.698	2.698

*When calculated f value is bigger than tabulated f value, the two sample groups have unequal variance. In this circumstance, the error in t-test inflates to various degrees. Thus, the t-test result is invalid and should not be used.

Table E-2: F-test and T-test results for gas consumption

Group	Calculation	Base Gas Consumption	Heating Gas Consumption	Overall Gas Consumption
1962-1964 vs. 1968-1973	f - calculated	1.74	0.90	1.32
	f - 0.05 (28/5)	4.50	4.50	4.50
	s	21.27	40.91	44.30
	t - calculated	1.202	0.24	0.356
	t - 0.05	2.035	2.04	2.035
	t - 0.01	2.733	2.73	2.733
1968-1973 vs. 1978-1979	f - calculated	0.51	2.03	5.95*
	f - 0.05 (28/4)	5.75	5.75	5.75
	s	23.29	39.24	42.73
	t - calculated	0.293	2.57	2.521*
	t - 0.05	2.037	2.04	2.037
	t - 0.01	2.739	2.74	2.739
1978-1979 vs. 1982-1984	f - calculated	11.72*	1.17	0.88
	f - 0.05 (4/3)	9.12	9.12	9.12
	s	24.11	27.52	19.03
	t - calculated	0.980*	1.58	3.525
	t - 0.05	2.365	2.37	2.365
	t - 0.01	3.499	3.50	3.499
before 1975 vs. After 1975	f - calculated	0.79	1.81	2.17
	f - 0.05 (34/8)	3.06	3.06	3.06
	s	21.94	38.58	41.42
	t - calculated	1.023	4.34	4.584
	t - 0.05	2.018	2.02	2.018
	t - 0.01	2.698	2.70	2.698

*When calculated f value is bigger than tabulated f value, the two sample groups have unequal variance. In this circumstance, the error in t-test inflates to various degrees. Thus, the t-test result is invalid and should not be used.

Appendix F

Estimated Energy Saving by PRISM, Simple Ratio Weather Normalization, and ENERGY STAR® Portfolio Management

Table F-1: Estimated energy saving by PRISM, SRWN and PM

Building ID	Retrofit Type	Estimated Retrofit Time	Energy Saving (kWh/m^2)		
			PRISM	SRWN	PM
Bldg1	Electricity & Gas	5/1/2010	38.1	61.6	46.7
3145-Retrofit 1	Gas	11/19/2010	64.5	49.9	99.3
3145-Retrofit 2	Gas	1/1/2008	75.6	64.5	36.7
3242	Electricity & Gas	11/1/2010	33.8	58.6	17.9
3477-Retrofit 1	Gas	10/12/2010	35.3	55.4	7.5
3477-Retrofit 2	Gas	1/22/2008	18.4	30.0	-8.0
3496-Retrofit 1	Gas	1/1/2011	42.1	29.5	-12.9
3496-Retrofit 2	Gas	12/31/2009	-15.6	-10.9	-12.6
3497-Retrofit 1	Gas	7/9/2009	60.9	48.5	87.4
3497-Retrofot2	Gas	1/1/2008	39.8	62.0	41.6
3624	Electricity & Gas	1/1/2010	-13.6	-14.7	-26.8
3798	Gas	11/1/2010	-45.6	-70.4	-17.5
3983	Gas	3/1/2011	35.4	11.5	13.2
4018	Electricity	1/1/2008	5.0	19.2	-5.6
4053	Gas	2/24/2010	92.0	82.5	89.6
4077	Electricity	3/1/2011	-9.7	-38.6	-1.6
4078	Gas	1/1/2010	54.7	57.4	83.1
4079	Gas	3/1/2010	64.2	57.9	63.7
4115	Electricity	11/1/2010	23.1	61.3	28.8
4358-Retrofit 1	Electricity	12/1/2009	38.6	17.0	57.1
4358-Retrofit 2	Gas	3/22/2008	74.4	74.0	41.9
4359-Retrofit 1	Gas	3/1/2011	-24.2	-30.3	-8.1
4359-Retrofit 2	Gas	3/1/2010	13.1	13.2	26.2
4359-Retrofit 3	Gas	3/1/2009	37.2	68.4	67.0
4741	Electricity & Gas	12/1/2009	-15.1	-19.4	19.1
4790	Electricity & Gas	3/1/2011	103.7	101.9	99.3
5521-Retrofit 1	Gas	3/1/2011	40.0	23.7	16.1
5521-Retrofit 2	Gas	3/1/2008	28.6	50.1	17.0
5528	Gas	1/1/2008	-24.8	-32.8	-34.0

5634	Electricity & Gas	3/1/2011	26.6	7.0	32.9
5645	Electricity	12/1/2008	-13.4	10.3	-14.5
5964	Gas	3/1/2011	21.9	7.8	33.4

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