Reducing Energy Consumption in Residential Buildings: The Impacts of Occupant Behaviour and Engaging Control Systems

By

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of

Master of Applied Science

In

Sustainable Energy Engineering and Policy

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Ottawa, Ontario

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Abstract

In Canada, buildings account for 35% of energy consumption and hold the largest opportunity for reducing energy consumption and greenhouse gas emissions. Occupant engagement poses one of the best solutions to reducing building energy consumption, with studies showing annual energy consumption can vary by up to 150% between active and passive occupants. In this thesis, an occupant-in-the-loop smart home energy system is designed and tested to explore how such systems can reduce building energy consumption through automation and occupant engagement. Simulation studies and a 125-participant survey were conducted to understand how to engage occupants to take action and their impact on home energy consumption. Insights from these studies were used to develop the smart home control system and reinforce design decisions. Testing results show 250 kWh of plug-load energy reduction and reinforce this projects conclusion that occupant-in-the-loop smart home energy systems can provide energy savings and increased occupant energy awareness/engagement.

Acknowledgements

I'd like to thank my thesis supervisors Professors Liam O'Brien and Scott Bucking for their support during my research journey. Their ability to provide direction and encouragement while also allowing me to be creative and lead my own research, was of tremendous value to me. They are role models for what it means to be great mentors and supervisors. I'd also like to thank my colleague Dr. Mohamed Ouf who provided guidance and support throughout my research.

This project was made possible by the team at Windmill Developments who allowed me access to data on their new Zibi development, including energy systems and building design information on specific residential buildings.

This project was supported by the Ontario Centers of Excellence, Windmill Development Group, and Natural Sciences and Engineering Research Council of Canada (NSERC).

Finally, my girlfriend and family with their support, encouragement, and positivity kept me going during the busy and stressful times of my research.

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List of Acronyms

AC	Air conditioning
ASHRAE	American Association of Heating, Refrigeration, and Air Conditioning Engineers
BAS	Building automation system
BPS	Building performance simulation
BREDEM	Building Research Establishment Domestic Energy Model
CO ²	Carbon dioxide
dB	Decibel
DHW	District hot water
EPW	EnergyPlus weather
ERV	Energy recovery ventilator
GJ	Gigajoule
gpm	Gallons per minute
GPS	Global Positioning System
GWh	Gigawatt hours
HEC	Household electricity consumption
HEMS	Household Energy Management System
HVAC	Heating, ventilation, and cooling
HRV	Heat recovery ventilator
IEA	International Energy Agency
IOT	Internet of things
kWh	Kilowatt hours
LEED	Leadership in Energy and Environmental Design
LED	Light emitting diode
MURB	Multi-unit residential building
NECB	National Energy Code for Buildings
OEB	Ontario Energy Board
PJ	Petajoule
RH	Relative humidity
SHEU	Survey of household energy use

1. Introduction

Hundreds of years of fossil fuel consumption have led to increased levels of greenhouse gas emissions in our atmosphere at levels never before seen in human history. This is leading to the biggest threat to our society in the 21st century, Climate Change. We have begun to see its effects, with catastrophic climatic events occurring on a regular basis across the world. There is no silver bullet to tackling this problem, however changing how we consume energy has a big role to play.

The building sector consumes the largest amount of energy compared to any other sector in the world, arguably providing the largest opportunity for reducing our global energy consumption [1]. Not surprisingly, it also holds a large opportunity for reducing greenhouse gas emissions as well. A 2009 report by the United Nations states that the building stock represents the most important opportunity to substantially cut greenhouse gas emissions, by virtue of the scale of the reductions that are possible and the economic returns from doing so [2]. Both energy performance as well as load management in buildings are issues that need to be addressed to help keep us below the 2°C of global warming above pre industrial levels (before year 1850) that the International Panel on Climate Change (IPCC) states is required to avoid catastrophic impacts of climate change [20].

1.1. Environmental Impact of Buildings

In 2016, there were about 14 million private dwellings in Canada, with multi-unit residential building (MURB) dwellings making up 4.7 million (33%) of the private units in Canada [3]. Trends in building permits indicate that even though single detached

homes currently make up the majority of private dwellings in Canada, it will not be long before multi-unit residential buildings close the gap. The proportion of single-detached houses has been declining over the past three decades and Statistics Canada reports that the construction pace of apartments, and especially condominium units, is accelerating, surpassing the number of single-detached houses constructed since 2012 [3, 4].

Buildings account for about 35% of the world's energy use, while transportation and the industrial sector only account for about 30% each [5 - 7]. In Canada, buildings account for roughly 35% of energy consumption, equating to about 3000 PJ (petajoules) or 833,300 GWh (gigawatt hours) of energy consumption [8, 9]. Residential buildings account for approximately half of this energy consumption, or 17.5% of Canada's total annual energy consumption at 1431 PJ of energy [10]. See Table 1.1 for a breakdown of the different dwelling types and their share of energy consumption.

Table 1.1: Energy consumption breakdown by dwelling type [10, 11]

Dwelling Type	Total Energy Consumption	% of Residential Building Energy Consumption	% of National Energy Consumption	Avg. Per Dwelling
Detached	1102 PJ (306 billion kWh)	78%	13.5	134 GJ
Multi-unit residential building	271 PJ (75 billion kWh)	19%	3.5	55 GJ
Other	57 PJ (15.8 billion kWh)	3%	0.5	111 GJ
Total	1431 PJ (397 billion kWh)	100 %	17.5	105 GJ

With an expanding global population and climate change disrupting the usual ecological cycles of our environment, energy consumption as well as water consumption and waste production must be addressed if industry truly wants to make buildings sustainable and

resilient. To do this, buildings need to not only become more efficient in how they operate, but ultimately limit their environmental impact and consumption to a rate that can be sustained by the planet. This entails designing and operating buildings to produce more or the equivalent amount of energy that they consume (net zero energy), produce close to no waste (zero waste), eliminate or offset CO₂ emissions (net zero carbon) and ensure water is consumed at a rate that can be replenished by the surrounding biosphere (net zero water).

Significantly reducing the impact buildings have on our environment through reduced energy consumption and greenhouse gas emissions is not a trivial pursuit and requires more than just efficient building systems, equipment, and appliances. What is now required to drive increased efficiencies and energy savings is for these building systems to communicate with each other intelligently about the various operational activities occurring within the built space, while at the same time engaging occupants to take action as well, and by doing so influencing how they behave.

1.2. Building Occupant Behaviour

Occupant behaviour represents one of the major sources of uncertainty related to energy consumption in buildings. Previous studies have shown it can increase annual energy consumption by up to 150% between active and passive occupant types [12]. It is considered one of the main six driving factors for energy consumption in buildings as identified by the International Energy Agency (IEA), Annex 53 [13], yet still poorly understood. These factors include climate, building envelope, building equipment,

operation and maintenance, occupant behaviour, and indoor environmental conditions [14].

As the performance of our buildings increases, so too will the impact of occupant behaviour, causing a large uncertainty in the energy savings potential of these high-performance buildings, regardless of the efficiency of systems. Studies have shown that highly engaged occupants in a conventional building can achieve equal or greater energy efficiency gains than passive occupants in a “green” or high-performance building [18, 19]. The impact of occupant behaviour spans all building energy systems (heating, ventilation, and cooling (HVAC), plug loads, hot water heating, and lighting) with certain systems becoming even more susceptible to differences in occupant behaviour as building envelope performance increases.

With so much uncertainty in building energy consumption attributed to occupant behavior, occupant engagement poses as an important solution to this challenge. A more holistic engineered system needs to be created that brings together both the various pieces of building equipment as well as occupants, to create an occupant-in-the-loop smart building system.

1.3. Smart Systems

Before smart building technology, a building automation system, which is essentially a centralized and networked system of hardware and software monitors that control a building’s systems (electricity, lighting, plumbing, HVAC, water supply, etc.), was the main control network for buildings, and still is for the most part today [15]. Building automation systems have advanced a great deal from the pneumatic controls that were

used in buildings during the 1950s. With microprocessors in the 1980s becoming small and inexpensive, building automation systems advanced from compressed air controls, to analog, to digital. Around the early 2000s, wireless sensor technology started to make wireless communication between components and controls possible, marking the dawn of the Internet of Things [15].

Over the past several years the term Internet of things (IOT) has grown in popularity for describing technologies that have the capability of not only sharing their data with one another, but also other information technology systems in order to gain a better understanding of the environment around them [16]. IOT has found its way into every facet of our economy from transportation and manufacturing to personal health and fitness, and now in our buildings.

It is these IOT technologies that, when integrated with the building automation system or connected into a single integrated system for homes and residential units and combined with feedback loops, add increased intelligence to our buildings. There is no single set of standards that define a smart building, however most definitions include driving operational efficiency and providing an optimum experience for building occupants.

Smart buildings are empowered by any technology that generates data that is associated with the building or its occupants. This includes but is not limited to: sensor driven data, video recognition, AI, human input, biometrics, smart phones, GPS, and robots/drones. This data can be associated with building operations such as lighting, HVAC, safety and security, irrigation, and equipment, however as our economy moves into a Third Industrial Revolution and Renewable Energy Economy (as expressed by world renowned

economist Jeremy Rifkin), increased demands are being placed on buildings now and into the future [21].

Buildings are evolving into the primary nodes of a Third Industrial Economy, where Internet technology and renewable energy are merging to create a lateral shift in the way we produce energy, transport goods, and communicate [21]. It is creating a reordering of human relationships—from hierarchical power to lateral power—that will impact the way we conduct commerce, govern society, and engage in civic life, and buildings are the nodes to connect it all [17]. The shift from hierarchical to lateral power means moving away from top down centralized economic systems to distributed and collaborative economic systems. This is causing buildings to evolve into more complex systems composed of onsite renewable energy generation, energy storage, information hubs, and vehicle fueling/charging stations. As a result, the way buildings are managed and controlled must evolve and change as well.

Buildings will be required to ensure all primary building functions are met in an efficient manner, an optimum occupant experience is achieved, and the added responsibilities of buildings in a Third Industrial Revolution economy are managed (ensure net zero emissions, net positive energy flow, resilience to impacts of climate change, etc.). To accomplish this, buildings will require integrated monitoring and control systems, occupant engagement, and up to the minute monitoring and corrective actions beyond the typical BAS system. In other words, buildings are going to require a robust smart building system to handle the new responsibilities being placed on them.

1.4. Problem Statement

Residential buildings make up 17.5% of Canada's overall energy consumption, with 397 billion kWh of energy consumption every year [10]. Multi-unit residential buildings are the fastest growing residential dwelling type, with Statistics Canada reporting that the construction pace of apartments, and especially condominium units is accelerating, surpassing the number of single-detached houses constructed since 2012 [3, 4]. High-performance buildings built to various building standards (LEED, Green Globes, etc.) utilize energy efficient equipment and systems to reduce the energy impact of the building. However, with previous studies showing occupant behaviour can impact annual energy consumption by up to 150%, this causes a large uncertainty in the energy savings potential of these high-performance buildings, regardless of the efficiency of systems. Studies have shown that highly engaged occupants in a conventional building can achieve equal or greater energy efficiency gains than passive occupants in a "green" or high-performance building [18, 19]. That said, as the energy performance of our buildings increases, the impact of occupant behaviour on building energy consumption increases as well. Their impact spans across all building energy systems (HVAC, plug loads, hot water heating, and lighting) with certain systems becoming even more susceptible to occupant behaviour as building efficiency increases.

The study conducted for this thesis aims to quantify the impact occupants have on the major residential building energy systems (in both conventional and high-performance buildings) in order to inform better building design decisions and the design of an occupant-in-the-loop smart home energy system. This includes what home energy

systems should be targeted as priorities by the smart home system, how the sensors and controls of this system need to connect and communicate with one another, opportunities for integration between various home energy systems, and the ideal user interface for providing information to occupants and creating engagement towards more energy efficient behaviour.

1.5. Thesis Layout

This thesis is divided into 10 chapters centered around the implementation of a smart home energy system with occupant in-the-loop controls.

With Chapter 1 providing an introduction to the problem, Chapter 2 provides a literature review of the past work done in the area of occupant in-the-loop smart building systems. It provides an understanding of past work done in the three key areas of residential energy consumption that this thesis covers: (1) the effect of occupant behaviour, (2) the impact of smart home energy systems, and (3) the design of smart home energy systems to incorporate occupant behaviour and engagement.

Chapters 3 and 4 analyze the impact of occupant behaviour on residential building energy consumption. The goal of these two chapters is to quantify the growing effect of occupants on residential building energy consumption and how home energy consumption breakdowns change depending on the type of occupants present in the space. These chapters also quantify which areas of household energy consumption are most susceptible to occupant behaviour and should be prioritized to address when designing the smart home energy system. Chapter 3 explores the comparison between the

impact of occupant behaviour in a conventional MURB unit compared to a high-performance MURB unit, whereas Chapter 4 conducts an analysis using a single building based on real project specifications. Chapter 4 also looks at the impact of occupant faults on building energy consumption, where a fault is an unexpected or unusual building system operation due to occupant behaviour. These occupant faults are areas of increased energy consumption potential that also need to be addressed in the design of the smart home energy system.

Chapter 5 consists of a 125-participant study where occupants were surveyed regarding their preferences when interacting with their home energy systems. Gaining a better understanding of how occupants interact with their building energy systems, how they prefer to receive information, and what motivates their behaviour, allows for designing the smart home energy system to meet the average users' needs and wants and successfully engaging them to take action.

Chapter 6 provides the details of both the back-end and front-end (user interface) portions of the smart home energy system design. The back-end design involves the development of the ideal metering and control configuration that will provide the data and information necessary to achieve energy reductions through automation and occupant engagement. The front-end of the smart home energy system development consists of the logic flow and communication formatting used to engage occupants. This design phase was informed by insights from Chapter 5.

Chapter 7 brings together the work from all the previous chapters with the implementation of the occupant in-the-loop smart home energy system. Both the implementation strategy and the results of its impact on residential energy consumption and building systems are presented. This chapter concludes with a discussion of what building systems are impacted most significantly from the implementation of this system as well as feedback from occupants as to its functionality.

Chapter 8 consists of a study on the application of a smart home energy system in reducing heating and cooling energy consumption through natural cooling. It analyses the feasibility of using an ERV with fresh air bypass connected to a smart home energy system to optimize the use of outdoor air to cool the indoor space of a condo unit instead of a mechanical means, which in the case of this analysis was a heat pump. This study helps substantiate how a smart home energy system can achieve energy savings that would otherwise not be achievable through a regular heating and cooling system.

This thesis concludes in Chapter 9 with a summary of the occupant and energy related benefits that, based on our results, are achievable through the implementation of a smart home energy system. It also provides the main research contributions from this work and recommendations for what further research in the area of smart home energy systems and occupant in-the-loop controls should focus on.

1.6. References

- [1] S. Holmes. “How LEED Saves Energy.” Internet:
<https://www.usgbc.org/articles/how-leed-saves-energy> , Oct. 2017 [1- Nov.-2017].
- [2] CaGBC. “Building Solutions to Climate Change.” Internet:
https://www.cagbc.org//cagbcdocs/2016_Building_Solutions_to_Climate_Change_Public.pdf , September 2016 [Accessed: 2-Nov-2017].
- [3] Statistics Canada. “Dwellings in Canada.” Internet:
<http://www12.statcan.gc.ca/census-recensement/2016/as-sa/98-200-x/2016005/98-200-x2016005-eng.cfm> , May 2017 [8-Nov-2017].
- [4] Statistics Canada. “Condominium Dwellings in Canada.” Internet:
http://www12.statcan.gc.ca/nhs-enm/2011/as-sa/99-014-x/99-014-x2011003_1-eng.cfm , 2016 [8-Nov-2017].
- [5] BOSS. “How Buildings Impact the Environment.” Internet:
<https://bosscontrols.com/buildings-impact-environment/> , 2017 [1-Nov-2017].
- [6] S. Holmes. “How LEED Saves Energy.” Internet:
<https://www.usgbc.org/articles/how-leed-saves-energy> , Oct 2017 [1- Nov-2017].
- [7] US Energy Information Administration. “How much energy is consumed in U.S. residential and commercial buildings.” Internet:
<https://www.eia.gov/tools/faqs/faq.php?id=86&t=1> , May 2017
- [8] National Round Table on the Environment and the Economy and Sustainable Development Technology Canada. “Energy Efficiency in Canada’s Commercial Building Sector.” Internet: <http://neia.org/wp-content/uploads/2013/04/commercial-buildings-report-eng.pdf> , 2009 [2-Nov-2017].
- [9] Statistics Canada. “Energy Supply and Demand 2014.” Internet:
<http://www.statcan.gc.ca/daily-quotidien/151210/dq151210e-eng.pdf> , Dec 2015 [2-Nov-2017].
- [10] Statistics Canada. “Households and the Environment: Energy Use.” Internet:
<http://www.statcan.gc.ca/pub/11-526-s/11-526-s2013002-eng.pdf> , 2013 [8-Nov-2017].
- [11] Natural Resources Canada. “Survey of Canadian Household Energy Use 2011 (SHEU report).” Internet:

- <https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2011/tables.cfm> , 2014 [8-Nov-2017]
- [12] Clevenger, C. M., J. R. Haymaker, and M. Jalili. “Demonstrating the Impact of the Occupant on Building Performance.” *J. Comput. Civ. Eng.*, vol. 28, no. 1, pp. 99–102, 2014.
- [13] Yan, D., W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, and A. Mahdavi. “Occupant behavior modeling for building performance simulation: Current state and future challenges.” *Energy Build.*, vol. 107, pp. 264–278, 2015.
- [14] Hong, T., Y. Chen, Z. Belafi, and S. D’Oca. “Occupant behavior models: Implementation and representation in building performance simulation programs.” *Build. Simul.*, no. July, 2017.
- [15] Control Solutions Inc. “The Ultimate Guide to Building Automation.” Internet: <http://controlyourbuilding.com/blog/entry/the-ultimate-guide-to-building-automation> , 2015 [9-Nov-2017].
- [16] H. Clancy. “10 companies moving up in Smart Buildings.” Internet: <https://www.greenbiz.com/article/10-companies-moving-smart-buildings> , Dec 2016 [8-Nov-2017].
- [17] The Office of Jeremy Rifkin. “The Third Industrial Revolution.” Internet: <https://www.foet.org/books/the-third-industrial-revolution/> , 2017 [8-Nov-2017].
- [18] Yan, D., W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, and A. Mahdavi. “Occupant behavior modeling for building performance simulation: Current state and future challenges.” *Energy Build.*, vol. 107, pp. 264–278, 2015.
- [19] D’Oca, S., V. Fabi, S. P. Corgnati, and R. K. Andersen. “Effect of thermostat and window opening occupant behavior models on energy use in homes.” *Build. Simul.*, vol. 7, no. 6, pp. 683–694, Jul. 2014.
- [20] Victor D. G., D. Zhou, E. H. M. Ahmed, P. K. Dadhich, and J. G. J. Olivier, “Introductory Chapter of Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.” *Cambridge University Press*. 2014.
- [21] TIR Consulting Group LLC. “Nord-Pas de Calais: Third Industrial Revolution – Master Plan 2013.” 2013

2. Literature Review

In reviewing the literature of past work, the studies that were analyzed explored the three key areas of residential energy consumption that this research covers: (1) the effect of occupant behaviour, (2) the impact of smart home energy systems, and (3) the design of smart home energy systems to incorporate occupant behaviour and engagement. Further references to the literature are provided throughout the chapters to substantiate the information and research covered in each particular section of the thesis.

2.1. Occupant Behaviour and Occupant Impact on Residential Building Energy Consumption

With many studies investigating the effect of occupant behaviour on commercial and residential building energy consumption [1 - 3], the ability for occupants to control a greater number of parameters in residential buildings makes it of greater interest for this particular study. Heating setpoints, for example, are often subject to more occupant control in residential buildings, unlike in commercial buildings where they are often centrally-controlled by operators [4]. Appliances, lighting and domestic hot water (DHW) are also heavily dependent on occupant behaviour, demographic profiles, and occupancy patterns [5]. Thus they can derive large variations in residential energy consumption. Previous studies showed energy consumption in residential units of the same multi-unit residential building (MURB) can vary by more than ten-fold, mainly because of usage patterns [28].

The effect of occupant behaviour on residential energy consumption can be classified into three main categories: 1) whole building metering and monitoring, 2) appliance and

lighting modelling, and 3) whole-building simulation. The first category focused on existing buildings by measuring their energy consumption and recording specific occupant parameters. For example, Andersen et al. [6] monitored window opening behaviour in 15 Danish dwellings, and concluded that indoor air quality and solar radiation were the main drivers behind it. Al-Mumin et al. [7] investigated summer air-conditioning use in 30 residences, and concluded that the thermostat set-points could vary from below 19°C to above 25°C, which would have a significant impact on their energy consumption. Bae et al. [8] investigated indoor temperatures in Korean residences, and found the average indoor ambient temperature ranged between 21 – 33°C in the summer, and 17 – 28°C in the winter. Relative to previous studies in Korea, indoor temperature in the heating period has been increasing over the past 20 years, and decreasing in the cooling period, suggesting more reliance on mechanical heating and cooling [8]. Huebner et al. [9] found that the average heating temperature in UK households was 19.8°C which is less than the default assumption of 21°C in the UK Building Research Establishment Domestic Energy Model (BREDEM). The heating durations during weekdays and weekends were also found to be less than default assumptions. Using a detailed occupant survey and measuring household energy consumption in Dutch residences, Guerra-Santin and Itard [3] showed that the duration of using heating systems had a stronger effect on energy consumption than temperature set-points. Findings of this study also suggested that some household characteristics, such as the presence of elderly occupants, had a significant effect on their energy consumption.

The second category of studies focused on modelling the effect of occupant behaviour on appliances and lighting consumption more specifically given their stronger relationship

with occupant behaviour. Using a bottom-up approach, Armstrong et al. [10] collected detailed data on appliances' consumption and durations for Canadian households. The data was used to develop electricity consumption profiles corresponding to three different types of occupants, which was then compared to actual measured data. Results showed that passive occupants can consume twice as much electricity as the average occupant, which was confirmed using data from existing buildings. However, measured data was only collected from four existing homes in Quebec, which may not be representative of the wider spectrum of occupant behaviour. Swan et al. [5] developed a hybrid model for estimating Canadian households' energy consumption, using artificial neural networks and a database of mechanical systems and thermal envelopes in Canadian households. The estimated electricity consumption for appliances and lighting was slightly higher than national models developed using a different approach. However, these findings illustrate the variability in electricity consumption due to occupant behaviour in Canadian households, although the study did not investigate MURBs.

The third category of studies relied on whole building performance simulations to highlight the effects of certain occupant parameters on residential energy consumption. D'Oca et al. [27] modelled three categories of occupant behaviour in residential buildings (active, medium, and passive) using a probabilistic approach that focused on window openings and thermostat adjustments. By comparing results with standard deterministic simulations, the study showed that energy consumption could increase by up to 61% when modelling different probabilities for occupant behaviour. A similar study by Bennet et al. [11], which focused on occupants' use of blinds in MURBs, showed they can lead to decreasing cooling loads. De Meester et al. [12] also investigated the effect of family size

and management of heating systems on Belgian households' energy consumption. By simulating different family sizes, occupancy profiles, and thermostat setpoints, the study showed these factors alone would have a strong effect on energy consumption, that ranged from 5% in non-insulated houses to 45% in houses built to Passivhaus Standards [12]. O'Neil and Niu [13] also found that variations in thermostat set-points, occupancy and lighting schedules had a 4% impact on the HVAC annual and peak energy consumption. The sensitivity analysis showed that thermostat setpoints had the highest effect on energy consumption. However, these studies did not investigate the effect of other occupant behaviours such as window opening, or use of appliances [12, 13]. Blight et al. [14] focused on residential Passivhaus buildings by generating occupancy, appliance-use, and door-opening profiles based on the United Kingdom Time of Use Survey. Results of the simulations were compared to measured heating consumption data from similar existing residences, which ranged from less than 5 kWh/m² to more than 40 kWh/m² with different occupancy profiles. By developing a multiple regression model, setpoint temperature, and appliance-use were shown to be the major estimators of total heating energy, while occupancy patterns were less significant [14]. While Blight et al [14] suggests that Passivhaus dwellings are not overly sensitive to occupant behaviour, by modifying the same occupant parameters in conventional and Passivhaus dwellings, we can compare the sensitivity to occupant behaviour between two different building types. This is covered in Chapter 3 of this thesis.

Research on this topic has focused on the impact of occupant behaviour on residential energy systems in subsets (i.e. heating and cooling system, lighting system, ventilation system, plug loads, etc.) but very little has been done to look at all these systems together

through a holistic analysis. On the basis that literature on this topic is fragmented, this thesis focuses on a whole energy system view of the impact of occupant behaviour as the first step to informing the design of the occupant in-the-loop smart home energy system.

2.2. Smart Home Systems Impact on Household Energy Consumption

The impact of smart energy systems on household energy consumption is divided into two main categories. The first category focused on smart home systems that enable a demand-response type system at home, whether to allow for peak flattening or optimized usage time during low electricity prices. For example, Zhuang et al. [15] investigated demand-response home systems that would allow for the optimal scheduling of home energy systems during times that real-time electricity prices were the lowest. Simulation results showed the potential of up to 35% savings on energy costs because of optimized appliance usage during times of low electricity costs. Barker et al. [16] also explored optimizing usage of home energy systems but for the purpose of flattening electricity demand during peak load times. Using a load scheduling device and software they developed, they addressed the scheduling of background loads (fridge, AC, dehumidifiers) to effectively decrease the average absolute deviation from the mean power by over 20% for all 4-hour periods that they measured where the deviation was greater than 400W. They also found that these background loads only account for 10% of the loads on a typical summer day while consuming nearly 60% of the energy. Zhou et al. [17] researched demand-response capabilities of a Smart Home Energy Management System (Smart HEMS) connected to a Smart Grid. They analyzed the various elements of the HEMS system which included grid connectivity, smart appliances, on site renewables

and storage, and how an HEMS can control all these various elements to provide the home owner with both electricity cost and peak load reductions. Findings from other research conducted on the ability of HEMS to reduce electricity costs and peak load demand show reductions of at least 20% on electricity operating costs and 30% on-peak load demand.

The second category of research investigated the home energy savings possible through the implementation of some element of a smart home system. Specific areas of energy savings potential were investigated as opposed to a holistic whole house energy system view. Agarwal et al. [18] investigated the implementation of a smart system to increase the energy efficiency of HVAC energy consumption in an office building, by incorporating occupancy patterns into the control loop of the HVAC system. Using simulation and data collected from the implementation of occupancy sensors in 10 offices, they showed potential energy savings of 10-15% using their system. This provides a good example of the type of energy savings possible through the merging of occupant behaviour and smart system implementation, however it only addresses one area of the energy system. Jahn et al. [19] and associates from Fraunhofer Institute for Applied Information Technology in Germany, explored the appliances side of building energy consumption in a home setting while also trying to integrate occupant behaviour change into their smart system. They integrated energy efficiency into a smart home infrastructure by creating an intuitive user interface for monitoring and controlling the energy consumption of various devices, with the hope that users would develop better strategies for saving energy and money with the provided information. Meyers et al. [20] examined two areas of inefficiencies that arise from the provision of energy services within a home, which they defined as inefficient delivery and inefficient conversion, and

quantified the amount of energy that they result in each year. They found these inefficiencies result in close to 40% of energy wasted and which they stated could be addressed by the implementation of smart home devices and systems. One shortcoming was that they did not outline how the devices would need to be implemented in order to communicate with one another as well as with occupants to create a smart home energy system and reduce the energy waste they had found.

2.3. Incorporating Occupant Behaviour in Smart Home Energy System Design

With so many smart home devices and systems coming onto the market with applications ranging from security to energy, the benefits to the user are not always clear, especially when these devices are not focused on as an integrated system. A recent study conducted by Wilson et al. [21] found that users lacked a clear sense of smart home benefits and expressed that a clear user-centric vision of smart homes is currently missing from a market that is being driven by developers. The question then becomes how practical are these smart home devices and systems and what are their benefits to users regarding reducing household energy consumption?

With occupants having such a big impact on energy consumption, it is arguably one of the most important areas to include in a smart home energy system, yet it is still not addressed in the design as much as it probably should be. For example, Bregman et al. [21] provided a universal implementation model for a smart home system, which he called smart home intelligence, consisting of a central management unit, user interface, home equipment and appliances interface, and external communication interface. However, in doing so the paper does not specify the types of energy benefits achieved by

this type of system or the specific benefits to users. Similar works by Meyers et al. [20] have also failed to connect occupant behaviour into the design of a smart home energy system.

Other researchers have explored elements of occupant engagement in reducing energy consumption. Spence et al. [23] used an online interface to provide participants with their own energy consumption information and found best engagement among participants when feedback was in the form of CO² emissions as opposed to kWh or cost. However, in this study the degree of engagement in terms of energy reduction was not quantified. In a study by Seligman et al. [24], they investigated the rate at which information feedback should be provided to occupants as part of a smart home energy system that engages occupants to take action. They found that home owners who received feedback in energy consumption multiple times a week as opposed to once a month, used 10.5% less energy. Beyond education, another strategy for occupant engagement is embedding gamification into the feedback provided to occupants from smart systems. The premise is that it will create longer lasting change in occupant behaviour than just education itself [25].

Gamification of energy consumption reduction in residential buildings can take the form of competitions against neighbors, goal setting, unlocking virtual levels and achievements, and getting ranked against other users on the same gamification platform. Mohr and Shultz et al. [25] in their paper on “Choosing effective behaviour change tools” showed the effectiveness of a number of strategies that can be incorporated into gamification to engage people to reduce their environmental footprint. One of these strategies is the use of commitments to instill behavior change. When occupants of households were asked to make a public commitment to conserve natural gas and electricity, they reduced natural gas and electricity by 15% and 20% respectively. Even

though these commitments were not actually published publicly, the fact that they thought they were, motivated occupants to take action. Public commitments also help to foster both social norms and social diffusion, which can create engagement amongst other occupants exposed to these effects [25].

Another example of the success of using gamification to increase occupant engagement, is from the Urban Sustainability Directors Network [25]. They implemented a “computer off program” in three government office buildings across three different states. The goal was to get employees to turn off their computers at the end of the day to save electricity. They used a combination of behavior change strategies which included education, signed commitments, and prompts to try and engage workers to turn off their computers. When workers only received the education email, turn off rates increased from 58% to 68% for computers and 21% to 23% for monitors [25]. However, when workers were asked to make commitments as well as received prompts in addition to the education email they received, turn off rates increased from 58% to 72% for computers, and 21% to 53% for monitors [25]. Research done by researchers in this field (Mohr and Shultz [25]), Vine [26], Seligman and Darley [24]), show the promising results of incorporating strategies to engage and impact behaviour change in a smart home energy system. In a recent report written by Vine et al. [26] where a series of gamification studies were reviewed, it was concluded that competitions are an effective way of changing behaviour and reducing energy consumption, however it is uncertain how long these occupant behaviour changes will persist. On average, savings were found to be 5% on electricity consumption and as high as 30% in some cases. These savings were measured during times that participants were actively participating in the competition/gamification program [26].

These findings of previous studies show the great work that is currently being done in the area of smart building research and design but also reveals the immaturity of the space.

There is a missing user-centric vision of smart homes, which was also mentioned by Wilson et al. [21], that literature on the topic of smart home energy systems has failed to address. It is for this reason that the research conducted for this thesis on the interaction between occupants and smart home energy systems to reduce home energy consumption, is much needed. Even though there is research on the impact of various occupant behaviour change strategies on energy reduction, there is a lack of research on what the energy consumption impacts would look like when these occupant engagement strategies are incorporated into a smart home energy system.

Along with the lack of literature on the connection between occupant behaviour research and smart home energy system development, is also limited research on the implementation of a smart home energy system in a real life setting to quantify potential energy impacts on home energy consumption. What was done in most cases was simulation scenarios. The research is fragmented on both the occupant behaviour impacts on residential energy consumption and impacts of a smart home energy system on home energy consumption. The analysis is on various subsets in both these areas and often simulated, with very limited work on analyzing them together and implementing them both as an integrated system. This is why the creation and implementation of an occupant in-the-loop controls system, informed by occupant behaviour and feedback, and implemented to produce real application results, is warranted.

2.4. References

- [1] Haldi, F. and D. Robinson. “The impact of occupants’ behaviour on building energy demand.” *J. Build. Perform. Simul.*, vol. 4, no. October 2014, pp. 323–338, 2011.
- [2] O’Brien, W., K. Kapsis, and A. K. Athienitis. “Manually-operated window shade patterns in office buildings: A critical review.” *Build. Environ.*, vol. 60, pp. 319–338, 2013.
- [3] Guerra-Santin, O., and L. Itard. “Occupants’ behaviour: determinants and effects on residential heating consumption.” *Build. Res. Inf.*, vol. 38, no. 3, pp. 318–338. 2010.
- [4] O’Brien, W., I. Gaetani, S. Gilani, S. Carlucci, P.-J. Hoes, and J. Hensen. “International survey on current occupant modelling approaches in building performance simulation?.” *J. Build. Perform. Simul.*, no. October, pp. 2008–2013, 2016.
- [5] Swan, L. G., V. I. Ugursal, and I. Beausoleil-Morrison. “Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique.” *Energy Build.*, vol. 43, no. 2–3, pp. 326–337, 2011.
- [6] Andersen, R. V., J. Toftum, and B. W. Olesen. “Long term monitoring of window opening behaviour in Danish dwellings.” no. June, pp. 22–24, 2009.
- [7] Al-Mumin, A., O. Khatatb, and G. Sridhar. “Occupants’ behavior and activity patterns influencing the energy consumption in the Kuwaiti residences.” *Energy Build.*, vol. 35, pp. 549–559, 2003.
- [8] Bae, C. and C. Chun. “Research on seasonal indoor thermal environment and residents’ control behavior of cooling and heating systems in Korea.” *Build. Environ.*, vol. 44, no. 11, pp. 2300–2307, Nov. 2009.
- [9] Huebner, G. M., M. McMichael, D. Shipworth, M. Shipworth, M. Durand-Daubin, and A. Summerfield. “The reality of English living rooms – A comparison of internal temperatures against common model assumptions.” *Energy Build.*, vol. 66, pp. 688–696, Nov. 2013.
- [10] Armstrong, M. M., M. C. Swinton, H. Ribberink, I. Beausoleil-Morrison, and J. Millette. “Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing.” *J. Build. Perform. Simul.*, vol. 2, no. 1, pp. 15–30, 2009.

- [11] Bennet, I., W. O'Brien, and H. B. Gunay. Effect of Window Blind Use in Residential Buildings: Observation and Simulation Study." *eSim*, 2014.
- [12] De Meester, T., A. F. Marique, A. De Herde, and S. Reiter. "Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe." *Energy Build.*, vol. 57, pp. 313–323, 2013.
- [13] O'Neill, Z., and F. Niu. "Uncertainty and sensitivity analysis of spatio-temporal occupant behaviors on residential building energy usage utilizing Karhunen-Loève expansion." *Build. Environ.*, vol. 115, pp. 157–172, 2017.
- [14] Blight, T. S. and D. a. Coley. "Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings." *Energy Build.*, vol. 66, pp. 183–192, 2013.
- [15] Zhuang, Z. "An Optimal Power Scheduling Method for Demand-Response in Home Energy Management System." *IEEE Transactions on Smart Grids*, vol. 4, pp. 1391- 1400, 2013.
- [16] Barker, S. Mishra, A. Irwin, D. Shenoy, P. and Albrecht, J. "SmartCap: Flattening Peak Electricity Demand in Smart Homes." *IEEE International Conference on Pervasive Computing and Communications.*, pp. 67 – 75, 2012.
- [17] Zhou, B. Li, W. Chan, K. and Cao, Y. "Smart home energy management systems: Concept, configurations, and scheduling strategies." *Renewable and Sustainable Energy Reviews.*, vol. 61, pp. 30 – 40, 2016.
- [18] Agarwal, Y. Balaji, B. and Gupta, R. "Occupancy Driven Energy Management for Smart Buildings. Build." *Sys.* pp. 1 – 6. 2010.
- [19] Jahn, M. and Jentsch, M. "The Energy Aware Smart Home." *5th International Conference on Future Information Technology*. 2010
- [20] Meyers, R. Williams, E. and Matthews, S. "Scoping the potential of monitoring and control technologies to reduce energy use in homes." *Energy and Buildings*. Vol. 42. pp 563 – 569. 2010.
- [21] Wilson, C. Hargreaves, T. and Hauxwell-Baldwin, R. "Smart homes and their users: a systematic analysis and key challenges." *Personal and Ubiquitous Computing*. Vol. 19. pp. 463 – 476. 2015.

- [22] Bregman, D. “ Smart Home Intelligence – The eHome that Learns.” *International Journal of Smart Home*. Vol. 4. Pp 35 – 46. 2010.
- [23] Spence, A. Leygue, C. Bedwell, B. and O’Malley, C. “Engaging with energy reduction: Does a climate change frame have the potential for achieving broader sustainable behaviour?” *Journal of Environmental Psychology*. Vol. 38. pp. 17 – 28. 2014.
- [24] Seligman, C., and Darley, J. M. “Feedback as a means of decreasing Residential Energy Consumption. *Journal of Applied Psychology*.” Vol. 62. pp 363 – 368. 1977.
- [25] Mohr, D., and Schultz, P. “Choosing Effective Behaviour Change Tools.” *2012 Behavior, Energy and Climate Change Conference Sacramento, California*. 2012.
- [26] Vine, E., and Jones, C. “A review of Energy Reduction Competitions: What have we learned?” *University of California, Berkeley*. 2015.
- [27] D’Oca, S., V. Fabi, S. P. Corgnati, and R. K. Andersen. “Effect of thermostat and window opening occupant behavior models on energy use in homes.” *Build. Simul.*, vol. 7, no. 6, pp. 683–694, Jul. 2014.
- [28] Yan, D., W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, and A. Mahdavi. “Occupant behavior modeling for building performance simulation: Current state and future challenges.” *Energy Build.*, vol. 107, pp. 264–278, 2015.

3. Impact of Occupant Behaviour on High-Performance Buildings vs Conventional Buildings

Note: This chapter uses text, tables, and figures from the author's paper titled "The effect of occupant behaviour on energy consumption in conventional vs. high-performance residential buildings" presented at the eSim 2018 Conference.

3.1. Introduction

Occupant behaviour is considered one of the main six driving factors for energy consumption in buildings as identified by the International Energy Agency (IEA), yet the least understood [2]. These factors include climate, building envelope, building equipment, operation and maintenance, occupant behaviour, and indoor environment conditions [3].

As building envelopes and equipment become more efficient, the contribution of appliances and lighting loads increases, thus the effect of occupant behaviour may become more pronounced [4]. High-performance buildings integrate and optimize all major high-performance attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity. To demonstrate their effectiveness, these buildings often follow certain standards or rating systems. One of these standards is the Passivhaus Standard which requires aggressive energy reduction targets to be met, often confirmed using whole building performance simulation [5]. In contrast, other rating systems such as Leadership in Energy and Environmental Design (LEED), gives points to a proposed building based on its percentage of energy cost savings relative to a certain baseline. In Canada, the baseline could be a building modelled similar to a building per the prescriptive path of the National Energy Code for Buildings (NECB) or American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard (ASHRAE) 90.1-2013 [6, 7]. For this study, conventional MURBs are considered as ones that follow

the baseline of NECB without any energy reduction measures. The high-performance MURB is modelled by following some of the guidelines for Passivhaus Standard, and on a case by case basis it is expected that the share of plug loads and hot water consumption will be greater than that of the conventional building. Moreover, it is also expected that there will be a large difference in energy consumption between the different occupant cases in conventional buildings vs. high-performance buildings. This is due to the fact that different heating and cooling temperature set-points are likely to have a greater effect on energy consumption in a lower performance building envelope.

The goal of this study is to demonstrate the growing effect of occupant behaviour in new high-performance MURBs. The first objective was to compare the effect of occupant behaviour on residential energy consumption between conventional and high-performance MURBs highlighting occupant parameters that should be addressed to reach net-zero or other ambitious energy reduction targets. The study also addresses the impact of occupants' purchasing decisions by modelling more efficient appliances, lighting and water fixtures in the high-performance building, and comparing their consumption to standard ones. The study focuses on a proposed MURB in Ottawa, Ontario by modelling proto-type residential units on the South and North façades. Three types of occupants are then defined as low, medium and high energy consumers based on typical Canadian household energy usage profiles or other North American references.

3.2. Methodology

To investigate the effect of occupant behaviour on energy consumption in conventional and high-performance MURBs, two generic residential units for each building were

simulated; one facing North and the other facing South, located in Ottawa, ON. The models were developed using BPS tool EnergyPlus in conjunction with Open Studio. Each unit had dimensions $W \times L \times H = 12 \times 10 \times 3 \text{ m}^3$ with a window of $W \times H = 6.0 \times 2.0 \text{ m}^2$ and sill height of 0.8 m. The boundary conditions for the interior surfaces were considered adiabatic, since they are adjacent to spaces with similar thermal conditions. The South-facing and North-facing wall in each of the respective units were exposed to outdoor conditions based on the EnergyPlus Weather (EPW) file.

The units were assumed to have an occupant density of $60 \text{ m}^2/\text{person}$ (i.e. two occupants per unit) per NECB (2015) [6]. The occupancy schedule was also created according to NECB which assumes lower occupancy (30%) between 8 AM and 5 PM on weekdays, and a slightly higher occupancy during these hours on weekends (50%). Figures 3.1 and 3.2 depict the operating schedules.

Figure 3.1: Weekday operating schedules

Figure 3.2: Weekend operating schedules

The assumption that occupancy rates do not drop to 0% for both weekday and weekend schedules aims to represent a wider variety of occupancy patterns, as some occupants may stay at home during these hours for various reasons.

Fresh air was supplied at a rate of 2.5 L/s person + 0.3 L/s.m² based on ASHRAE Standard 62.1 [7]. The HVAC system was ideal load system for both models, with heat recovery and an outdoor air economizer enabled for the high-performance model.

Reported heating and cooling energy consumption is the heating and cooling energy supplied to the space. Auxiliary energy required for HVAC fans/pumps was not included.

Table 3.1: Design inputs for the conventional and high-performance MURB units

Input design parameter	Conventional MURB	High-performance MURB
Exterior Wall U-Value (W/m ² K)	0.247	0.12
Windows U-Value (W/m ² K)	2.2	0.7
Windows SHGC	0.45	0.7
Windows visible transmittance	0.8	0.8
WWR	37%	30%

3.2.1. Occupant Cases

Besides the three occupant cases described above, a baseline case was also simulated using the default occupant related parameters set forth in NECB 2015 for MURBs, such as thermostat setpoints, lighting, plug loads and DHW loads. Table 3.2 provides an overview of the occupant related parameters used for each case.

Table 3.2: Occupant related inputs for each case

Occupant Parameter		Baseline	Active Occupant	Average Occupant	Passive Occupant
Heating setpoint °C		22	19	21	22
Heating set-back temp °C		18	18, 16	18	22
Heating set-back schedule		12 AM - 6 AM	12 AM - 6 AM, & 8AM - 5PM	12 AM - 6 AM	No set-back
Cooling setpoint °C		24	No cooling	23	23
Cooling set-up temp °C		24	No cooling	No cooling	23
Cooling set-up schedule		No set-up	No cooling	8 AM - 5 PM	No set-up
Blinds		No blinds	Blinds used extensively to reduce cooling loads, and increase privacy.	Blinds used arbitrarily, mainly just for privacy at night.	Blinds rarely used with limited change in their position throughout the year.
Window use		No windows opened	Windows used optimally during cooling and shoulder seasons	Windows used arbitrarily, and only opened at night	Windows are rarely opened (0% window opening)
Lighting W/m ²	High-performance	5.5	1.0	1.3	1.5
	Conventional	5.5	3.2	4.2	4.9
Equipment W/m ²	High-performance	5	3.2	4.5	5.6
	Conventional	5	4.3	6.6	7.9
DHW W/person	High-performance	500	231	340	483
	Conventional	500	340	500	710

3.2.2. Heating and Cooling Temperature Set-Points

Temperature set-points for the average occupant (case 2) were based on the NRCan Survey of Household Energy Use in Canada [8]. Most households in Ontario set their thermostat to 21°C in the winter and 23°C or more in the summer [8]. For heating, the other cases deviated by -2°C for active occupants and +1°C for passive occupants, thus they would still be within the acceptable comfort range of ASHRAE 55-2013. For cooling, active occupants were assumed to rely only on natural ventilation and not air conditioning which is not unusual for MURB residents in Ontario [8].

When modelling temperature set-backs in the winter the following was included: both daytime and nighttime set-backs for active occupants (case 1), only night-time set-backs for average occupants (case 2), and no set-backs for passive occupants (case 3). For temperature set-ups in the summer, active occupants were not included as they were assumed to switch off mechanical cooling completely during the summer. Average occupants, were assumed to shut-off cooling during the day on weekdays before leaving their residences. Passive occupants were assumed to have no set-ups and they keep cooling set-points unchanged throughout the day. It is important to note here that a study by Meier et al. [9] surveyed household occupants in the United States and found that almost 90% of respondents rarely or never adjusted their thermostats.

3.2.3. Blind Usage

With many new MURBs having increasingly large window to wall ratios, cooling energy loads will become even more sensitive to how occupants use their blinds [10]. Bennet et al. [10] showed that most blind opening actions occurred in the morning before occupants

left for work (7 AM – 9 AM) and most closing actions around the time that occupants get home from work (5 PM – 7 PM) [11]. These findings were the basis for the average occupant blind use schedule (case 2), where it was assumed that they use blinds on a habitual routine (i.e. closing them at night) rather than specifically for reducing cooling demand which was assumed for active occupants (case 1). Passive occupants (case 3) were assumed to rarely use their blinds or change their positions. Therefore, the average daily occlusion observed by Bennet et al. [10] was used where, the north-facing units were found to have an average daily occlusion rate of 60%, and 80% for south-facing units.

3.2.4. Window Opening

Active occupants (case 1) were assumed to rely only on natural ventilation for cooling by opening windows throughout the cooling and shoulder seasons. For average occupants (case 2), windows were assumed to be opened only in the evenings, between 6 PM and 6 AM, if the indoor temperature was around the cooling set-point (22 – 23°C). Passive occupants (case 3), were assumed to rarely operate their windows and to simulate this scenario, the windows were considered not open at all.

3.2.5. Plug Loads

One of the main research questions investigated in this study was the effect of occupant appliance purchasing decisions on their unit energy consumption. Therefore, conventional MURB units were assumed to only include standard appliances, while high-performance units were assumed to include Energy Star certified appliances, which use less electricity. Phantom loads were also considered by assuming that active occupants (case 1) always

unplug appliances after they use them, while the other two occupant cases were assumed to always leave their appliances plugged in after use.

A bottom up approach was then implemented to generate plug load profiles for each occupant case similar to the process described in Armstrong et al. [12]. Based on appliance types, and estimated durations of use, a target daily plug loads consumption was calculated for each case. Tables 3.3 and 3.4 provide a list of the appliances considered in this study, their estimated power consumption and use durations which were collected from Canadian and American Government publications (Natural Resources Canada and Lawrence Berkley National Laboratory) [13,14]. Average use durations for the smaller appliances were used for the average occupants (case 2), while active occupants were considered to use the same smaller appliances for 50% less time and unplug them afterwards, if reasonably possible. Passive occupants (case 3) were assumed to use the same smaller appliances for 50% more time to account for frequent patterns of leaving appliances on while they are not being used. The major appliance use durations were based on cycle times for energy star rated appliances as well as Federal regulation standard cycles times. Active occupant use durations were estimated as being just below energy star ratings, passive occupant behaviour use durations were estimated at being just above federal standards, and average occupants use durations estimated in the middle of the two [20],[21],[22].

In this study, the same appliance use schedule based on the NECB 2015 was used for all cases. Afterwards, the equivalent peak plug load for the energy models that would correspond to the target daily plug load consumption for each case was calculated, as shown in Table 3.2. However, the baseline case used the receptacle load specified in NECB 2015. The disadvantage in this approach is that it does not account for the time of

day of using appliances which could change the impact of their heat gains on mechanical heating or cooling. More detailed analyses of plug load consumption profiles in Canadian households at lower resolutions are outside the scope of this study, and were investigated previously in Canadian households [12, 15].

Table 3.3: List of appliance related parameters for each case – no efficiency rating

Appliance	Power Consumption		Durations		
	Standard		Active Occupant	Average Occupant	Passive Occupant
	Power (W)	Phantom load (W)			
Television	150	6.4	2 hr/day	4 hr/day	6 hr/day
Cable box	25	17	2 hr/day	4 hr/day	6 hr/day
Stereo	14	8	1 hr/day	2 hr/day	3 hr/day
Coffee Maker	560	1.14	0.25 hr/day	0.5 hr/day	1 hr/day
Dryer	3867 (2.9 kWh/cycle)	1.4	16 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Dishwasher	650 (1.3 kWh/cycle)	1.3	52 cycle/yr.	108 cycle/yr.	182 cycle/yr.
Washer	225 (0.45 kWh/cycle)	2.7	52 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Computer	45	8.9	5 hr/day		
Range & Oven	3000	2.2	0.8 hr/day		
Toaster	1500		0.1 hr/day		
Microwave	1500	2.8	0.22 hr/day		
Blender	1500		0.1 hr/day		
Refrigerator	55	1.7	20 hr/day + 4 hr/day standby		

Table 3.4: List of appliance related parameters for each case – Energy Star Rating

Appliance	Power Consumption		Durations		
	Energy Star		Active Occupant	Average Occupant	Passive Occupant
	Power (W)	Phantom load (W)			
Television	47	0.4	2 hr/day	4 hr/day	6 hr/day
Cable box	14	0.4	2 hr/day	4 hr/day	6 hr/day
Stereo	7	0.1	1 hr/day	2 hr/day	3 hr/day
Coffee Maker	N/A	N/A	0.25 hr/day	0.5 hr/day	1 hr/day
Dryer	2800 (2.1 kWh/cycle)	1.4	16 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Dishwasher	550 (1.1 kWh/cycle)	1.3	52 cycle/yr.	108 cycle/yr.	182 cycle/yr.

Washer	125 (0.25 kWh/cycle)	2.7	52 cycle/yr.	136 cycle/yr.	208 cycle/yr.
Computer	N/A	N/A	5 hr/day		
Range & Oven	2500	2.2	0.8 hr/day		
Toaster	900		0.1 hr/day		
Microwave	900	2.8	0.22 hr/day		
Blender	900		0.1 hr/day		
Refrigerator	50	1.7	20 hr/day + 4 hr/day standby		

3.2.6. Domestic Hot Water

Domestic hot water was calculated using a similar bottom-up approach, by estimating daily hot water demand for each unit with two occupants. Daily hot water demand profiles were generated based on estimates for using showers, bathroom and kitchen faucets which represent most hot water demands in residential buildings. To further demonstrate the effects of occupants' purchasing decisions, high-performance units were assumed to be fitted with low-flow fixtures, while conventional units were fitted with standard fixtures. The United States Environmental Protection Agency (US EPA) [16] published flow rates for standard and low-flow fixtures in residential buildings, were the basis of our assumptions.

The average shower usage of Canadians is around 8 minutes/day, which was the basis for estimating the average occupants' consumption (case 2). Previous studies showed that occupants could reduce their showering energy usage by between 20 and 30%, by receiving real-time feedback on their usage [17]. Therefore, shower use durations for active occupants (case 1) were assumed to be 6 minutes/occupant/day, whereas passive occupants (case 3) were assumed to be 10 minutes/occupant/day. For kitchen and bathroom faucets, the average use duration was also 8 minutes/day, which was used for the average occupant (case 2). Active occupants were assumed to deviate from this

average by 50% less and passive occupants by 50% more. Table 3.4 provides an overview of the assumed flow-rates and durations of using water fixtures per occupant in each case. Once the total DHW flow rate was calculated for each case, the NECB 2015 DHW schedule was used to calculate the equivalent domestic hot water demand in Watts/occupant for each unit, to correspond to the target DHW consumption for each case. Only 10% of the energy available in the hot water was assumed to contribute to internal heat gains [18].

3.2.7. Lighting

The United States Department of Energy published estimates for residential lighting consumption in different regions of the US and found the average number of lamps per household for MURBs was around 25 lamps for north-eastern states, which are closest to Ontario [19]. The average daily hours of use per lamp in these states is 1.7 hours/day which formed the basis of the assumptions for average occupants (case 2). Active occupants (case 1) were assumed to have the same number of lamps, however, the daily duration of use per lamp was assumed to be 1.3 hours which is the lowest duration within all US states. In contrast, the daily duration of use per lamp was assumed to be 2 hours for the passive occupants (case 3) which is the highest duration within all US states.

Although the number of lamps per residential unit was fixed for all cases and for the conventional and high-performance MURB, lamp types were assumed to be different between the buildings. Conventional MURB units were assumed to be fitted with incandescent lamps with lamp power of 60 W/lamp [19]. High-performance MURB units were assumed to be fitted with LED bulbs having lamp power of 15 W/lamp, which provides the same level of luminance as a 60 – 100 Watt incandescent light bulb [19].

Based on these assumptions, the target daily lighting consumption was calculated for each case within each MURB unit. Afterwards, the NECB lighting schedules were used to calculate the equivalent lighting power inputs for the energy models that correspond to the target lighting consumption for each case as shown in Table 3.2.

3.3. Results

Total energy consumption for all three occupant cases in both conventional and high-performance buildings increased between active and passive occupant behaviour. In conventional buildings, total energy consumption increased by 58%, from 44.6 GJ (active occupants) to 70.5 GJ (passive occupants). In the high-performance building, total energy consumption increased by 55%, from 18.4 GJ (active occupants) to 30.2 GJ (passive occupants).

When compared to the base case that was modelled, it can be seen that for the conventional building, active occupants consumed 28% less energy and passive occupants consumed 12% more energy, with average occupants almost even with the base case, consuming 6% less energy. For the high-performance building, all three occupant cases consumed less energy than the base case, with active occupants consuming 68% less energy, average occupants consuming 61% less energy, and passive occupants consuming 51% less energy. Figures 3.3 and 3.4 provide a breakdown of the total energy consumption of each case by major end use, and the percentage that these values make up of the total.

Figure 3.3: High-performance building energy consumption for different occupant cases

Figure 3.4: Conventional building energy consumption for different occupant cases

3.4. Discussion

Results showed that the high-performance building consumes less total energy than the base building by at least 50% for all three occupant behaviour cases. Most significant was the decrease in end use energy consumption from heating, which was lower in the high-performance building. This is due to the high-performance building having a better insulated envelope as per passive house standards, which helps to keep its heating loads much lower regardless of the different occupant set-points modelled here. Cooling loads for the high-performance average occupant case are significantly closer to the base case than heating loads, which is likely due to the increased requirements for cooling as internal gains increase and the envelope better retains heat. Lighting was also significantly lower for all three cases compared to the base case. This is a result of not only use of efficient lighting, but also different lighting density assumptions.

For the conventional building, energy consumption results compare more closely to the base case. The average occupant case (case 2) consumed about the same total energy as the base case, with slight variations in how energy consumption was broken up by end use. Active occupants (case 1) showed the significance of the impact occupant behaviour has on energy consumption, with total energy consumption almost 30% less than the base case. With both the base case and conventional building built to the same standard, these savings in case 1 show how active occupant behaviour can significantly reduce energy consumption. Most of the savings were from a reduced heating load and no cooling load, which was the result of lower set-points and efficient setbacks. However hot water and

lighting use was the source of some significant energy savings for active occupants, with consumption 63% less than the base case lighting and hot water consumption.

In both conventional and high-performance building cases, heating loads decrease significantly while cooling loads increase between the three cases. This can be explained by the fact that as hot water use, appliance use, and lighting use increase, internal heat gains increase and therefore space heating requirements decrease. However, this also creates higher demand for cooling which is what causes an increase in cooling energy consumption. All other end uses can be seen to increase in both cases for both conventional and high-performance cases.

Comparing the results of the high-performance building to that of the conventional building, provides insights into how occupants impact energy consumption as building envelopes increase in performance. As seen in the base case, the heating load makes up 58% of the dwellings overall energy consumption. On a case by case basis, the conventional building's heating load represents a significantly larger portion of the dwellings overall energy consumption relative to the high-performance building.

Interestingly, cooling loads make up similar portions of the total energy consumption in both conventional and high-performance buildings, with case 1 the same and cases 2 and 3 by 2%. Lighting energy consumption does not make up a significant amount of total energy consumption in either building type, and is about 2% lower for every case in the high-performance building.

The comparison of the two different building types shows hot water and appliances making up an increased share of total energy consumption in the high-performance building compared to the conventional. In all three occupant cases, appliance energy

consumption and hot water consumption make up about a 10% higher share in the high-performance building type compared to the conventional building.

The reason for appliance and hot water consumption making up a significantly larger percentage of the overall energy consumption in high-performance buildings is largely due to the better insulated envelope of high-performance buildings allowing for decreased heating demand. For an average occupant living in a high-performance building, this means hot water heating and appliance use account for 58% of total energy use. This can be compared to the average occupant in a conventional building where hot water and appliance use comprise 36% of energy consumption, and it can be seen that as buildings become more efficient, the energy breakdown drastically changes. More specifically, heating load share decreases while other loads such as hot water heating and appliance use increase. This means that changes in how occupants use hot water and appliances make a more significant impact in changing end use energy consumption in high-performance buildings as opposed to conventional buildings.

3.5. Conclusion

With the push for better performing building envelopes to increase heating and cooling energy efficiency, the breakdown of end use energy consumption changes. Heating, though still significant, has been shown here to decrease by 20 percentage points across the three occupant behaviour scenarios. Hot water consumption and appliance usage on the other hand, have each been shown to increase by 10 percentage points each across the various occupant scenarios, both of which occupants can influence significantly.

What needs to be done is to consider how to influence occupant behaviour in a way that improves energy efficiency or design buildings to be less susceptible to occupant behaviour. This analysis shows that both high-performance and conventional buildings are very susceptible to occupant behaviour, with close to a 60% increase in energy consumption between active and passive occupant behaviour.

With results showing a decreasing share of heating in total energy by about 20 percentage points and hot water and appliance usage increasing shares by around 10 percentage points each, high-performance buildings are changing the way we need to look at energy conservation and what end uses need more attention.

Chapter 3 explored the impact of both occupant behaviour as well as building design on residential unit end use energy breakdown. Chapter 4 will look purely at occupant behaviour using a single building design based on specifications of a building currently under development by our industry partner, Windmill Developments. Chapter 4 will examine the impact of occupant behaviour on energy consumption as well as occupant faults such as lights left on and windows left open.

3.6. References

- [1] Clevenger, C. M., J. R. Haymaker, and M. Jalili. “Demonstrating the Impact of the Occupant on Building Performance.” *J. Comput. Civ. Eng.*, vol. 28, no. 1, pp. 99–102, 2014.
- [2] Yan, D., W. O’Brien, T. Hong, X. Feng, H.B. Gunay, F. Tahmasebi, and A. Mahdavi. “Occupant behavior modeling for building performance simulation: Current state and future challenges.” *Energy Build.*, vol. 107, pp. 264–278, 2015.
- [3] Hong, T., Y. Chen, Z. Belafi, and S. D’Oca. “Occupant behavior models: Implementation and representation in building performance simulation programs.” *Build. Simul.*, no. July, 2017.
- [4] Hoes, P., J. L. M. Hensen, M. G. L. C. Loomans, B. de Vries, and D. Bourgeois. “User behavior in whole building simulation.” *Energy Build.*, vol. 41, pp. 295–302, 2009.
- [5] De Meester, T., A. F. Marique, A. De Herde, and S. Reiter. “Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe.” *Energy Build.*, vol. 57, pp. 313–323, 2013.
- [6] NECB. “National Energy Code of Canada for Buildings.” *National Research Council of Canada*. 2015
- [7] ASHRAE. “Energy Standard for Buildings Except Low-Rise Residential Buildings (I-P edition).”
- [8] Natural Resources Canada (NRCAN). “Survey of Household Energy Use 2011 – Detailed Statistical Report” Government of Canada. 2014.
- [9] Meier, C. Aragon, T. Peffer, D. Perry, and M. Pritoni. “Usability of residential thermostats: Preliminary investigations.” *Build. Environ.*, vol. 46, no. 10, pp. 1891–1898, Oct. 2011.
- [10] Bennet, I., W. O’Brien, and H. B. Gunay. “Effect of Window Blind Use in Residential Buildings: Observation and Simulation Study.” *eSim*, 2014.
- [11] Azar, E. and C. Menassa. “Agent-based modeling of occupants and their impact on energy use in commercial buildings.” *J. Comput. Civ. Eng.*, vol. 26, no. August, pp. 506–518, 2011.

- [12] Armstrong, M. M., M. C. Swinton, H. Ribberink, I. Beausoleil-Morrison, and J. Millette. "Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing." *J. Build. Perform. Simul.*, vol. 2, no. 1, pp. 15–30, 2009.
- [13] Natural Resources Canada (NRCan). "Micro-HydroPower Systems: A buyers guide." pp. 45. 2004.
- [14] Lawrence Berkley National Laboratory. "Default Energy Consumption of MELs." *Home Energy Saver and Score: Engineering Documentation*. 2000
- [15] Swan, L. G., V. I. Ugursal, and I. Beausoleil-Morrison. "Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique." *Energy Build.*, vol. 43, no. 2–3, pp. 326–337, 2011.
- [16] US EPA. "WaterSense ® High-Efficiency Lavatory Faucet Specification Supporting Statement." pp. 1–8. 2007.
- [17] Swiss Federal Office of Energy. "ewz-Amphiro Study: The effectiveness of Real-Time Feedback" pp.2. 2014.
- [18] Hendron, R. and C. Engebrecht. "Building America House Simulation Protocols." *U.S. Department of Energy, NREL*. pp. 12. 2010.
- [19] Gifford, W. R., M. L. Goldberg, P. M. Tanimoto, and M. E. Poplawski, "Residential Lighting End-Use Consumption Study: Estimation Framework and Initial Estimates." *U.S. Dep. Energy*, 2012.
- [20] Energy Star. "Certified Products, Dishwashers." *United States Government: EPA and DOE*. Internet: <https://www.energystar.gov/products/appliances/dishwashers> , January 2016
- [21] Energy Star. "Certified Products, Clothes Dryer." *United States Government: EPA and DOE*. Internet: https://www.energystar.gov/products/appliances/clothes_dryers , January, 2015.
- [22] Energy Star. "Certified Products, Clothes Washer." *United States Government: EPA and DOE*. Internet: <https://www.energystar.gov/products/appliances/dishwashers> , February, 2018.

4. Impact of Occupant Behaviour and Occupant Faults on Residential Energy Consumption

4.1. Introduction

Chapter 3 showed how different occupant behaviours can so significantly vary the energy consumption of specific residential energy systems such that a passive occupant in a high-performance MURB consumes as much as an average occupant in a conventional MURB. It also showed the potential variation in total energy consumption between an active occupant and a passive occupant in both a conventional and high-performance MURBs. With the results from this simulation study showing a large potential for energy savings if occupants can be successfully engaged to operate their home more energy efficiently, a secondary study was conducted that focused specifically on the top areas for greatest energy reductions through occupant behaviour change. Analysis focuses on two occupant behaviour extremes (active and passive behaviour), modeling them in a building based on specifications from a MURB project currently in progress by our industry partner, Windmill Developments. The study also focused on quantifying the impact of occupant faults on the energy consumption of a MURB unit with two occupants, and what building systems were most susceptible to these faults.

4.2. Methodology

4.2.1. Modelling Specifications

A single condo unit was modelled using specifications from a MURB under development in Ottawa. This unit was modelled both on the North and South side of the building to quantify variations in sun exposure. Building specifications were provided by Windmill

Developments for their Block 13 building as part of their new Zibi development. This included a ventilation rate of 20 L/s, infiltration of 5.7 L/s, as well as total daily internal heat gains of 6.2 kWh. Heating and cooling systems were modelled with ideal load systems. Table 4.1 below outlines the specifications for the units that were modelled and Figure 4.1 depicts a mockup that was made in Sketchup of the modelled unit. All energy modelling was done in EnergyPlus.

Table 4.1: North and South condo unit specifications

Specification Type	South Side Specifications	North Side Specifications
Window Shading Coefficient	0.35	0.35
Window SHGC	0.30	0.30
Window U value	0.33 Btu/hr-ft ² °F (1.87 W/m ² K)	0.33 Btu/hr-ft ² °F (1.87 W/m ² K)
Window to Wall Ratio (WWR)	40%	40%
Window Visible Transmittance (VT)	0.8	0.8
Window Frame U value (aluminum)	0.88 Btu/hr-ft ² °F (5 W/m ² K)	0.88 Btu/hr-ft ² °F (5 W/m ² K)
Balcony	6 ft. (1.8 m) deep (wall to edge), 100% of wall width	6 ft. (1.8 m) deep (wall to edge), cover 50% of North side windows
Wall U value	0.059 Btu/hr-ft ² °F (0.33 W/m ² K)	0.059 Btu/hr-ft ² °F (0.33 W/m ² K)
Roof R value	31 hr-ft ² °F/Btu (5.5 m ² K/W)	31 hr-ft ² °F/Btu (5.5 m ² K/W)

Figure 4.1: Isolated South unit with North unit seen in background

4.2.2. Occupant Behaviour Cases and Related Inputs

Occupants' interactions with the building include adjusting thermostat settings, opening or closing windows, turning lights on/off, pulling window blinds up or down, switching plug loads on or off, and consuming domestic hot water [1]. Therefore, the models were subject to different occupant assumptions regarding all interactions with the building. To standardize the assumptions and represent a wide variety of occupant types, two cases of occupants were investigated 1) active occupant and 2) passive occupant. Only two occupants were modeled as that was all that was required to establish the range in which occupants can influence energy consumption of the major home energy systems. The occupancy schedule for all cases was modelled based on a 9 AM - 5 PM work day, with occupants leaving in the morning and returning in the evening. The two different occupants were defined as follows:

Case 1: Active Occupants – These are individuals who frequently interface with their unit control systems as well as the built environment that surrounds them. Their actions are primarily motivated by improving energy efficiency and reducing consumption, while still maintaining a space which is comfortable by taking various adaptive measures. They have some degree of knowledge on how their behaviour in buildings can either negatively or positively impact energy and water consumption, and make an effort to consciously think about their decisions from an environmental standpoint.

Case 2: Passive Occupants – These are individuals who rarely interface with their unit control systems or built environment, and rely on the indoor environment to be conditioned based on automated mechanical systems or set-points which are rarely

changed unless their comfort is disturbed. They have a lack of knowledge for how their behaviour and indoor environment settings impact energy efficiency or the environment. The sections that follow describe the various inputs related to each occupant case that has been summarized in Table 4.2.

Table 4.2: Occupant related inputs for each case

Occupant Parameter		Active Occupant	Passive Occupant
Heating set-point, °C		19	22
Heating set-back temp, °C		18	21
Heating set-back schedule		12 AM - 6 AM	12 AM - 6 AM
Cooling set-point, °C		25	22
Water Heating		Shower time: 6 min Low flow faucet: 1.5 gpm (0.00009 m ³ /s)	Shower time = 10 min Low flow faucet: 1.5 gpm (0.00009 m ³ /s)
Blinds		Blinds used extensively to reduce cooling loads, and increase privacy.	Blinds rarely used with limited change in their position throughout the year.
Window use		Windows used optimally during cooling and shoulder seasons	Windows are rarely opened (0% window opening)
Dishwasher		215 cycles/yr. [2]	365 cycles/yr. [2]
Dryer		122 cycles/yr. (0.5x Energy Star Standard, assumed air drying during months of low humidity) [3]	416 cycles/yr. [3]
Washer		283 cycles/yr. [4]	416 cycles/yr. [4]
Oven		On for just under 1 hr. every day (estimate based off of data from National Resources Canada and Lawrence Berkley National Laboratory) [5, 6]	
Electronics	On	On time estimates based on data from National Resources Canada and Lawrence Berkley National Laboratory [5, 6]	
	Off (Phantom Load)	Phantom loads are unplugged	Phantom loads are not unplugged

4.2.2.1. Heating and Cooling Temperature Set-Points

Temperature set-points for the average occupant reported by an NRCan Survey of Household Energy Use in Canada show that most households in Ontario set their thermostat to 21°C in the winter and 23°C or more in the summer [7]. For heating, an active occupant was estimated to have a set-point 2°C less than this and a passive occupant 1°C more than this, thus they would still be within the acceptable comfort range of ASHRAE 55-2013. For cooling, active occupants were assumed to set a 25°C temperature set-point, representing the high end of temperature set-points based on the NRCan study and 22°C for passive occupants representing the lower end of household temperature set-points found in the study [7].

When modelling temperature set-backs in the winter, nighttime set-backs for both active and passive occupants were included, at 1°C less than their temperate setpoints. Both active and passive occupants were assumed to have no set-ups during the cooling season and kept their cooling set-points unchanged throughout the day. It is important to note here that a study by Meier et al. [8] surveyed household occupants in the United States and found that almost 90% of respondents rarely or never adjusted their thermostats.

4.2.2.2. Blind Usage

With many new MURBs having increasingly large window to wall ratios, cooling energy loads will become even more sensitive to how occupants use their blinds [9]. Bennet et al. [9] showed that most blind opening actions occurred in the morning before occupants left for work (7 AM – 9 AM) and most closing actions around the time that occupants get home from work (5 PM – 7 PM). These findings were the basis for the active occupant blind use schedule, which was assumed to be a habitual routine during the cooling season

to help reduce solar gains. Passive occupants were assumed to rarely use their blinds or change their positions. Therefore, the average daily occlusion observed by Bennet et al. [9] was used where, the North-facing units were found to have an average daily occlusion rate of 60%, and 80% for South-facing units.

4.2.2.3. Window Opening

Active occupants were modelled as using natural ventilation for cooling by opening windows throughout the cooling and shoulder seasons. Windows were assumed to be opened based on the occupancy schedule and if cooling was required while outdoor temperatures were below the indoor temperature setpoint (25°C). Passive occupants were assumed to rarely operate their windows and to simulate this scenario, the windows were considered not open at all.

4.2.2.4. Plug Loads

Since the units that were modelled for this study were based on the green development specifications from our industry partner Windmill Developments, it is assumed that Energy Star Appliances and electronics will be used where possible. For this reason the unit was modelled using available Energy Star certified appliances, and electronics, which use less electricity. Phantom loads were also considered by assuming that active occupants always unplug appliances after they use them, while passive occupants were assumed to always leave their appliances plugged in after use.

Based on appliance types, and estimated durations of use, a target daily plug loads consumption was calculated for each case. Table 4.3 provides a list of the appliances considered in this study, their estimated power consumption and use durations which were collected from Canadian and American Government publications (National

Resources Canada and Lawrence Berkley National Laboratory) [5, 6]. For appliances, estimated cycles per year were based on Energy Star and United States Department of Energy data. Average amount of cycles for the different appliances as well as phantom loads being turned on or off were the basis for which active and passive occupant plug load energy consumption differed. Passive occupants were assumed to leave all electronics plugged in at night, and therefore consume phantom electricity while active occupant were assumed to disconnect these phantom loads.

This approach did not account for the time of day of using appliances which could change the impact of their heat gains on mechanical heating or cooling. More detailed analyses of plug load consumption profiles in Canadian households at lower resolutions are outside the scope of this study, and were investigated previously in Canadian households [10, 11].

Table 4.3: List of appliance and electronic related parameters for each case

Appliance	Power Consumption		Usage Duration	
	Power (W)	Phantom Load (W)	Active Occupant	Passive Occupant
Television	186	17	4 hrs/day	4 hrs/day
Cable box	25	17	4 hrs/day	4 hrs/day
Game Console	26	12	1 hr/day	1 hr/day
Stereo	14	8.3	2 hrs/day	2 hrs/day
Clock Radio	2	0.0	24 hrs/day	24 hrs/day
Coffee maker	560	1.1	0.5 hrs/day	0.5 hrs/day
Laptop Computer	54	15	5 hrs/day	5 hrs/day
LCD Monitor	27	1.4	5 hrs/day	5 hrs/day
Printer	9	5.1	0.15 hrs/day	0.15 hrs/day
Toaster	900	0.0	0.1 hrs/day	0.1 hrs/day
Microwave	900	2.8	0.22 hrs/day	0.22 hrs/day
Blender	900	0.0	0.1 hrs/day	0.1 hrs/day
Dryer	2800 (2.1 kWh/cycle)	1.4	122 cycles/yr	416 cycles/yr
Dishwasher	550 (1.1 kWh/cycle)	1.3	215 cycles/yr	365 cycles/yr
Washer	125 (0.25 kWh/cycle)	2.7	283 cycles/yr	416 cycles/yr
Range/oven	2500	2.2	0.8 hrs/day	0.8 hrs/day
Refrigerator	50	1.7	20 hrs/day	20 hrs/day

4.2.2.5. *Domestic Hot Water*

Domestic hot water was calculated using a similar bottom-up approach, by estimating daily hot water demand for each unit with two occupants. Daily hot water demand was based on estimates for using showers, bathroom and kitchen faucets which represent most hot water demand in residential buildings. Units were assumed to be fitted with low-flow fixtures, with rates of 1.75 gpm for shower heads and 1.5 gpm for faucets. These flow values were based on published standards for low flow fixtures from The United States Environmental Protection Agency [12].

The average shower usage of Canadians is around 8 minutes/day, however previous studies showed that occupants could reduce their showering energy usage by between 20 and 30%, by receiving real-time feedback on their usage [13]. Therefore, shower use durations for active occupants were assumed to be 6 minutes/occupant/day, whereas passive occupants were assumed to be 10 minutes/occupant/day. For kitchen and bathroom faucets, the average use duration was also 8 minutes/day, so active occupants were assumed to deviate from this average by 25% less and passive occupants by 25% more.

The next section of the simulation methodology outlines how the impact of occupant faults on residential energy consumption was determined. The purpose of which is to understand what areas of residential energy systems are most susceptible to large increases in energy consumption and then address them through smart home energy system design.

4.2.3. Identification and Simulation of Occupant Faults

In addition to identifying which systems and equipment occupants have the most impact on, part of this studies analysis was focused on understanding the effect occupant faults such as windows being left open in the winter, use of external electrical heating devices, electronics and lights being left on, etc. on residential energy consumption. Using EnergyPlus once again and the unit specifications provided earlier in this chapter, a simulation based assessment of the energy impact from occupant faults was conducted. There were six occupant fault types simulated for this analysis, which included window operation, supplemental heating use, lighting, appliances and electronics, water faucet use, and temperature set-points. The following sections outline how each of these were modelled and assessed.

4.2.3.1. Window Operation

When windows are used and opened optimally, they can provide great benefit in terms of energy savings to the HVAC system, especially for cooling. However, this is not always the case, and window opening actions can occur to provide fresh air into the space, regardless of the temperature inside or outside.

To quantify the potential impact of sub optimal window use, a continuous window opening scenario was modelled where windows were opened for fresh air purposes when individuals arrived home from work in the evenings. Table 4.4 summarizes the parameters for this case.

Table 4.4: Window opening parameters

Parameter	Value
Total window area	10 m ²
Window fraction open	0.5 m ² (5% of window area)
Duration	5pm – 7pm every day

4.2.3.2. *Supplemental Heating*

The next area that was analyzed, was how the introduction of supplemental heating sources would affect energy consumption. Once again using the occupancy schedule of an individual who works a 9-5 job, the occupant was assumed to operate their electric heater for four hours in the evenings during the winter months of November, December, January, February, and March. Most heaters feature a low to high setting for the amount of heat that they can output, which means a power draw of 750 – 1500 Watts. To account for this, an average of 1125 Watts was taken to be the power consumption of the heater.

4.2.3.3. *Lighting*

One of the most common, yet easily addressed occupant inefficiencies is leaving the lights on when a room is not occupied. To quantify this, a variety of scenarios were modelled as follows to obtain a range of possible energy impacts that can occur.

Case 1: Two lights left on overnight (3x per week) - This would model an occupant leaving lights on in the garage, outside, in their living room, etc. and going to sleep without knowing they were left on. The duration of this case is 8 hrs/night.

Case 2: Two lights left on (could be in hall, closet, or bathroom) while at work (5x per week). This represents the scenario of a person leaving for work (8 hrs.) and forgetting to turn lights off somewhere in the house. The duration of this case is 8 hrs/day.

Case 3: A single light left on all year long (5x per week). This represents the possibility of an outdoor light or a bathroom light that is never turned off, whether due to convenience or safety reason.

All the lights modelled for these scenarios were LED bulbs with a power consumption of 12 Watts. 12-Watt LED bulbs were chosen as they provide the equivalent light output in lumens as a 60 – 100 Watt incandescent light bulb.

4.2.3.4. Plug Loads

The occupant faults analyzed for plug loads examined the impact of on off behaviour for six specific electronics that are more common to be left on than others. The electronics included an LCD computer monitor, cable box, gaming console, audio music system, ink jet printer, and TV. For each electronic, the energy consumption difference between normal appliance operation based on appliance/electronic daily usage times from Canadian and American Government publications (National Resources Canada and Lawrence Berkley National Laboratory) and alternative use cases were analyzed [5, 6]. Case 1 refers to electronics turned off both during sleep and while occupants are away at work, and Case 2 refers to electronics turned off only when occupants are sleeping. Table 4.5 provides a breakdown of the power consumption of each electronic device, and its subsequent on/off schedule for each case.

Table 4.5: Device power consumption and plug load cases

Device	Power (W)	Phantom Load (W)	Base	Case 1	Case 2
Computer LCD display	27.6	1.4	On: 5 hrs	Phantom load off 16 hrs/day (while occupant is sleeping and at work)	Phantom load off 8 hrs/day (while occupant is sleeping or at work)
Digital cable box	24.6	17.8	On: 4 hrs		
Game console	23.3	1.0	On: 4hrs		
Music system	14.0	8.2	On 2 hrs		
Ink jet printer	9.16	5.26	On: 0.2 hrs		

Phantom loads were included in the total energy consumption for this analysis to achieve a fair comparison between on and off scenarios of electricity consumption. Final values

are presented in additional energy use that each of the two cases consume on top of normal operation.

4.2.3.5. *Temperature Set-Points*

In this final area of analysis for occupant faults, the impact on energy consumption of higher-than-normal temperature set-points in the winter for heating and lower-than-normal temperature set-points in the summer for cooling were analyzed. A heating and cooling base case scenario was modelled for comparative purposes. The parameters for the two scenarios are outlined in Table 4.6.

Table 4.6: Temperature set-points for base case and fault scenarios

	Base Case	Fault Case
Heating	21°C with 18°C setback	24°C with 22°C setback
Cooling	24°C	21°C

4.3. Results and Analysis

Passive occupants consumed a far greater amount of energy when compared to active occupants, and in the case of energy consumption of a clothes dryer and electronic devices, more than double. When analyzing overall energy impact of the two different occupant behaviour extremes, the largest difference in energy use consumption was in heating and cooling, with a difference of 1150 kWh. Following this was water heating with an energy difference of 870 kWh, and dryer usage and electronics, each with an energy difference of just over 600 kWh. These results provide a starting point for understanding which areas occupants have the most impact on energy consumption, and in what priority action should be taken to address how occupants use energy in these areas. Figure 4.2 below provides a breakdown of the energy consumption for active and

passive occupants. Blind and natural ventilation operation by active occupants provide some degree of energy savings, totaling more than the annual energy consumption of a refrigerator.

Figure 4.2: Energy consumption of active and passive occupants

A large amount of additional energy can be consumed given various occupant faults, with an additional 700 kWh in some cases. Half of the occupant faults analyzed resulted in additional energy consumption of between 600 and 700 kWh as can be seen in Figure 4.3. With LED light bulbs, occupant faults associated with lighting have much less of an impact on energy consumption as opposed to occupant faults associated with heating or cooling energy consumption. The greatest amount of energy consumption associated with a lighting occupant fault resulted in 105 kWh/yr. compared to an occupant fault associated with heating and cooling energy consumption which would result in at the very least, just under 600 kWh/yr, a 600% increase.

Figure 4.3: Energy consumption of occupant faults

Results show that occupant faults associated with high efficiency lighting such as LEDs do not have a large impact on overall energy consumption compared to faults associated with heating and cooling energy consumption. Depending on the severity of occupant faults associated with plug loads, it is possible that they can cause a large impact on energy consumption comparable to the effects of increased heating temperature set-point.

4.4. Conclusion

This simulation study was conducted on the impact of occupant behaviour on residential building energy consumption. Two different occupant types (active and passive) were modelled to determine the energy systems most susceptible to large variations in energy consumption due to varying occupant behaviours. This study also focused on identifying what home energy systems are most susceptible to large amounts of wasted energy from occupant faults (leaving windows open, leaving lights on, etc.). Findings from this study show that the occupant faults associated with heating and cooling cause the largest

amounts of wasted energy, with an average of 600 -700 kWh/yr. of additional energy consumption per fault. Phantom plug loads, hot water heating, dryer usage, and heating and cooling were most impacted by changes in occupant behaviour. Findings from this chapter will help to provide a better understanding as to which energy systems should be a priority within the smart home energy system design and where to implement sensors and controls as a first priority.

4.5. References

- [1] Hong, T., Y. Chen, Z. Belafi, and S. D'Oca. "Occupant behavior models: Implementation and representation in building performance simulation programs." *Build. Simul.*, no. July, 2017.
- [2] Energy Star. "Certified Products, Dishwashers." *United States Government: EPA and DOE*. Internet:
<https://www.energystar.gov/products/appliances/dishwashers> , January 2016
- [3] Energy Star. "Certified Products, Clothes Dryer." *United States Government: EPA and DOE*. Internet:
https://www.energystar.gov/products/appliances/clothes_dryers , January, 2015.
- [4] Energy Star. "Certified Products, Clothes Washer." *United States Government: EPA and DOE*. Internet:
<https://www.energystar.gov/products/appliances/dishwashers> , February, 2018.
- [5] National Resources Canada (NRCan). "Micro-Hydropower Systems: A buyers guide." pp. 45. 2004.
- [6] Lawrence Berkley National Laboratory. "Default Energy Consumption of MELs." *Home Energy Saver and Score: Engineering Documentation*. 2017.
- [7] National Resources Canada (NRCan) "Survey of Household Energy Use 2011." 2014.

- [8] Meier, C. Aragon, T. Peffer, D. Perry, and M. Pritoni. "Usability of residential thermostats: Preliminary investigations." *Build. Environ.*, vol. 46, no. 10, pp. 1891–1898, Oct. 2011.
- [9] Bennet, I., W. O'Brien, and H. B. Gunay. "Effect of Window Blind Use in Residential Buildings: Observation and Simulation Study." *eSim*, 2014.
- [10] Armstrong, M. M., M. C. Swinton, H. Ribberink, I. Beausoleil-Morrison, and J. Millette. "Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing." *J. Build. Perform. Simul.*, vol. 2, no. 1, pp. 15–30, 2009.
- [11] Swan, L. G., V. I. Ugursal, and I. Beausoleil-Morrison. "Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique." *Energy Build.*, vol. 43, no. 2–3, pp. 326–337, 2011.
- [12] US EPA. "WaterSense® High-Efficiency Lavatory Faucet Specification Supporting Statement." pp. 1–8. 2007.
- [13] Swiss Federal Office of Energy. "ewz-Amphiro Study: The effectiveness of Real-Time Feedback" pp.2. 2014.

5. The behaviour of occupants when interacting with building energy systems

5.1. Introduction

With the push for buildings to become more energy efficient to the point of reaching net zero energy consumption, many different technical and operational solutions are being developed and deployed. One area of the built environment that is gaining increasingly more attention yet still requires more understanding and research, is the building occupant. Different occupant behaviours can cause orders of magnitude difference in energy consumption between two of the exact same buildings. It is because of this fact that designers at Windmill Developments are looking to better understand how they can engage occupants in their new Zibi development to change their behaviour to becoming more energy efficient. With Windmill's goal of being one of the greenest developments in the world, the impact of occupant behaviour on energy consumption could significantly impact its attainment.

The simulation studies from Chapters 3 and 4 showed what home energy systems are most impacted by differences in occupant behaviour and how susceptible certain systems are to occupant faults. This provided a good basis as to the type of questions that needed to be asked as part of this study to gain insights as to how occupants interact with their home energy systems and how occupants can be engaged to adopt more energy efficient behaviour. To accomplish this, a study was conducted on the interaction of homeowners and renters with their home energy system, consisting of 125 respondents. The goal of this anonymous survey aimed at homeowners and renters is to develop an understanding of the best ways to engage residential building occupants to take action towards reducing

energy consumption in their home/unit apartment (dwelling). Through this survey, the following research questions will be answered:

1. What are the biggest motivators for occupants to take action in becoming more sustainable (reducing their energy consumption, reducing their water use, reducing waste generation, etc.)?
 - 1.1. An additional related question is: Are occupants currently concerned with their energy consumption?
2. How can energy consumption feedback be formatted in a way that makes it easy for occupants to understand, while also being informative and engaging?
 - 2.1. An additional related question is: How literate is the typical occupant about energy and related building systems?

5.2. Methodology

To investigate the behaviour of occupants when interacting with building energy systems in their residential dwellings, a 30-question survey was conducted. This survey was broken down into six major sections which were developed based on the kind of insights necessary to better engage occupants to change their energy behaviour to become more efficient. The proposed method of interfacing with occupants to engage them and provide them with the necessary information is through either a smartphone application or a wall mounted display. The sections below outline the development of the survey and how it was administered.

5.2.1. Survey Development

The development of the occupant behaviour survey was done by first understanding the key questions that needed to be answered which would then inform how best to engage occupants to change their energy behaviour to become more efficient. Based on previous research studies as well as common knowledge of everyday human behaviour, how people act and what they prefer is not always intuitive and can sometimes seem irrational, that is until the reasoning behind the behaviour is further investigated. It is because of this, that real occupant feedback from homeowners and renters was required to truly understand their home energy knowledge and behaviour preferences. This is what motivated the creation of the following sections of the survey.

Section 1 and 2- General information about occupant and dwelling: These first two sections of the survey consist of questions that collect information regarding age of participant, type of occupation, type of home ownership, and area of ownership. The purpose of these sections is to allow for the stratification of results by various occupant and home characteristics to see how they affect the occupants preferences and choices. As a result, it may be possible to draw certain correlations between age group and type of home ownership to certain types of occupant behaviour. This could be useful for better understanding what types of information and designs are better suited for certain age groups, occupation types, home owners etc. to change their energy consumption behaviour.

Reed [1] found that young people prefer to have more options and choices when making a decision whereas older adults preferred half the number of choices and the elderly even less than older adults. This is one example of how age makes a

difference in the amount of information an occupant might prefer to receive.

Being able to understand how behaviour differs between different occupant groups can allow for tailoring a different experience (information, design, motivators, etc.) to that user.

Section 3 - Motivation for energy conservation: The purpose of this section of the survey is to understand what motivates occupants to take action. This allows for structuring the information provided to occupants about their energy consumption to better feed what motivates them. In some cases, the answer to this question may be based on age and occupation. Providing information that motivates occupants to take action is the most critical piece for making a change in behaviour possible. One method that has been used with success in motivating individuals to take action in areas that they would normally find difficult to do so, is through gamification. Gamification applies the typical elements of game playing (trophies, medals, competition, rules of play) and applies it to other areas of activity, in everything from finance, marketing, teaching, and health and fitness. Using the feedback provided in this section of the study and merging it with the concepts of gamification, could provide a powerful means for incentivizing occupants to take action in becoming more sustainable.

Section 4 - Understanding building and energy systems: The purpose of this section of the survey is to understand in what format, and how detailed, the information provided to occupants should be so that they can understand it to the best of their ability. The thinking behind this is that if information, no matter how useful, is too complicated for an occupant to understand, they will dismiss it and likely not pay attention to it.

Microsoft CEO Satya Nadella said that “The true scarce commodity of the near future will be human attention.” He was probably speaking to the fact that his company had just finished a recent study of Canadian media consumption that had concluded the average Canadian attention span has fallen to 8 seconds [2].

Attention span was defined by the study as “the amount of concentrated time on a task without becoming distracted”. The shrinking attention span of society makes this section of the survey so important. Understanding what information people do and do not know allows for optimizing the type of information sent to occupants, both in quantity and content, in order to keep their attention.

Section 5 - Desired information to receive about building energy consumption:

The purpose of this section of the survey is to better understand what information is best to have more frequently and more prominently displayed on the smart home energy system user interface. Determining the information occupants feel they are missing to make better decisions about their energy consumption, helps to better understand what type of data should be collected and then presented to occupants. It is also necessary to understand the frequency at which occupants would want to receive information to provide benefit and prevent annoyance.

From his book “The Organized Mind”, McGill University psychology professor Daniel Levitin states that we take in at least five times more information everyday than we did in 1986 [3]. Occupants are continuously flooded with more and more information, which is why it is so important that the information provided to occupants through a smart home energy system is concise and only contains the most necessary information to spark occupant action. The amount and frequency

of information that should be sent to occupants is a very important item of understanding if a system is to support engagement and not detract from it.

Section 6 - Preferred way of receiving information: The purpose of this section of the survey is to understand what information display types occupants find most visually appealing and engaging. The better data is able to be presented so that it is easy to understand, the more likely occupants will be engaged to take action.

Based on the understanding that different methods of packaging information can make it easier and quicker to absorb than others, the way energy consumption and conservation due to occupant actions are presented to occupants, is an important topic of investigation. It is critical in the case of engaging occupants because it will affect the speed and ease at which occupants understand the information, how enjoyable the experience is, how visually pleasing the information they receive appears to them, and their likelihood to continue to want to receive further feedback and communications.

Based on the understanding that there are various types of learning styles (visual, aural, verbal, etc.), this section of the study looks to determine how the majority of occupants prefer to see information presented.

5.2.2. Administering Survey

Once the survey was developed as outlined above, it was sent for ethics approval from the Carleton University Research Ethics Board. With approval obtained at the end of 2017, the survey was administered starting January 2018. The following avenues were used to recruit public participants.

- LinkedIn: The survey was shared through networks on LinkedIn to solicit responses.
- Organizations working with the Carleton University research team.
 - BGIS: The survey was shared with the management team from the real-estate management company BGIS who is collaborating with Carleton University on research efforts for improving building energy efficiency. This management team then shared it with other members of the BGIS organization in both Ontario and Quebec.
 - Windmill Developments: The survey was shared with the project team working on Windmill Developments newest real-estate development (Zibi) which Carleton University researchers have been working with them on. They sent the survey out to all the people who had purchased condo units as of January 2018, consisting of around 75 occupants.

5.3. Results and Analysis

5.3.1. Population Stratification

When analyzing population stratification, there were two questions asked of participants to help provide researchers insights into how different occupant characteristics affect behaviour and preferences. The first question asked age of occupant, and results showed a relatively even distribution across most of the various age ranges. Figure 5.1b shows a graphical depiction of the participant age breakdown.

The second question solicited responses regarding type of occupation. Most noteworthy and considered further in this analysis is that 50% of participants classified themselves as working in the field of Engineering/Manufacturing and Technology, and about 25% of participants labeled themselves as working in the field of Business/Management and Administration as can be seen in Figure 5.1a. Given the large number of participants in these two categories, analysis was done to see if occupants from these two categories had noticeably different answers than the rest of the participants from various occupational backgrounds.

Figures 5.1a and 5.1b: Breakdown of survey participants occupations (5.1a - left) and Age (5.1b -right)

5.3.2. Dwelling Characteristics

70% of respondents owned their dwelling as opposed to rented. A majority of respondents (60%) lived in detached homes, with semi-detached homes making up the next largest participant group at 20%, and those living in high rise or mid-rise apartments making up the remaining 20%. This breakdown closely represents the Canadian residential building stock, as about 54% of Canadians live in single detached homes and 33% live in multi-unit residential buildings (high rise and mid-rise apartment buildings) [4 - 6]. Figures 5.2a and 5.2b provide a breakdown of the dwelling characteristics of study participants.

How participants receive their energy bills is also an important factor to better understanding certain behaviour characteristics/preferences of participants. 80% of

respondents either receive their energy bills monthly or bi-monthly, meaning that they do not receive real-time feedback about their energy consumption and how much they pay is directly linked to how much they consume (unlike people whose energy costs are included in their monthly rent or condo fees). This type of billing likely causes occupants to care more about their energy consumption compared to someone who pays a fixed cost for their energy regardless of the amount they consume.

The area in which occupants lived was broken down by local and regional characteristics.

A majority of participants either lived in urban (42%) or suburban (45%) areas.

Regionally, 55% of those that participated in the survey were from Ontario, 38% from outside of Ontario but within Canada, and 6% from outside of Canada.

Figure 5.2a and 5.2b: Type of homeownership (5.2a - left), Type of home (5.2b - right)

5.3.3. Motivation for Energy Conservation

Half of respondents stated that reducing their monthly energy costs was their biggest motivator for reducing energy consumption. Of the remainder, 35% of participants stated reducing their impact on the environment as their primary motivation and 14% said that the impact energy has on the health of loved ones was their primary motivating factor.

The breakdown of results can be seen graphically in Figure 5.3.

Figure 5.3: Occupants motivations for reducing their energy consumption

In most age groups only 43% of participants stated cost as their motivating factor for energy conservation, however for those aged 25-34, more than 60% stated this as their motivating factor. It is possible that the added financial pressures this age group feels being early in their career and possibly still paying student loans, might contribute to the increased importance they put on cost savings over environmental or human health factors.

Similar results were seen when results were analysed by home ownership type and how this affected participants choices. Close to 60% of renters stated cost as their motivating factor for reducing energy consumption compared to 47% of owners. This discrepancy in results between ownership type might again be related back to the influence of age and the different challenges faced at different stages of a person's life. In this study, 70% of renters are below the age of 34, which means that they could still be in school, just graduated school and paying off student debt, or finding their way early in their career. As a result, finding ways to reduce their spending and save money will likely be of top priority for this subset of participants, which makes sense why cost would be one of their motivators for reducing energy consumption.

5.3.4. Factors Impacting Motivation for Energy Conservation

Mentioned briefly under the survey development section, gamification and competition can be used to some degree to help influence occupant behaviour and motivate them to take action. Competition allows humans to satisfy the need to win, provides the opportunity or reason to improve their performance, motivates them to put forth greater effort that can result in higher levels of performance [7]. The annual campus conservation nationals held at Princeton University is a great example of the use of competition to help motivate energy conservation. A month-long competition sees occupants in the campus residence buildings compete to see who can reduce the most energy consumption, with 1000's of kWh/day conserved [8].

In this study, participants were asked whether they would be interested in seeing how their energy consumption compared to their neighbour's average energy consumption or their own average energy consumption. Only 16% of participants said that they would only be interested in seeing how they compare to their own average energy consumption, with 84% interested in seeing their neighbour's energy consumption. With occupants interested in their neighbour's energy consumption, this provides good indication that this information can be used to incentivize friendly competition between occupants with a high level of success.

Another big piece of being able to incentivize behaviour change in occupants is to have relevant and timely information to provide to them in order to base any sort of competition or gamification around. When asked if they felt having real-time information about their energy consumption would be more useful to them in reducing their energy consumption than monthly bills, 63% agreed, 22% somewhat agreed and only 5% did not.

This seems to indicate that occupants are open to the idea of receiving real-time information as well as learning more about their energy consumption and ultimately how they can reduce it. Figure 5.4 summarizes these results below.

Figure 5.4: Occupants agreement on whether real-time energy information is better than monthly.

5.3.5. Energy Consumption Concern

Only 5% of participants stated that they did not use any methods in their home to conserve energy. The other 95% of participants stated that they took action on one or more methods of conserving energy throughout the year. When asked whether they would be willing to wear a sweater in the winter to allow for a lower heating temperature set-point and reduced heating energy consumption, 80% of respondents were in some variation of agreement that they would be willing to wear a sweater in the winter, with approximately 60% percent in agreement and 20% in somewhat of agreement.

These results show that occupants are thinking about energy conservation, however it is hard to determine the degree of concern they have. Occupants state they are willing to make different choices in terms of the clothing they wear to reduce energy consumption, which is a positive indicator that occupants are willing to make certain changes to reduce energy consumption and therefore must have some degree of concern for how much they are consuming.

5.3.6. Understanding Building Energy Systems

Trying to influence a behaviour change towards more efficient energy use requires presenting occupants with information that they can understand as quickly and easily as possible. Most participants (50%) felt that receiving their daily energy consumption in the form of a percent reduction compared to their usual consumption in kWh would be the most intuitive and easy to understand for them - for example, the message: “you reduced your daily energy consumption by 10% today”. Following this was about 28% of respondents who felt it easiest to understand their energy conservation information in the form of an analogous amount. This could be for example: “you saved enough energy to power your light bulbs for a day” or “you saved enough energy to power your laptop for a week”. Finally, 22% of respondents felt that receiving their information in the form of kWhs saved would be easiest for them to understand. For example: “you conserved 2 kWhs of electricity today”.

Analyzing the breakdown of this information by occupation type shows how occupant preferences for receiving energy information can vary based on their type of work. Graphically represented in Figure 5.5, those working in the engineering and technology space favour receiving information in the form of kWh much more than any of the other occupation types. Close to 50% of those in business and administration favour receiving energy conservation information in the form of an analogous amount, which is 30 percentage points more than those in Engineering and almost 20% more than those in other occupation types. These differences most likely correlate to the fact that those with an Engineering background have a better understanding of how much 2 kWhs of electricity is and would prefer to see their energy information displayed in this manner or

as a percent reduction compared to an analogous amount. Business and administration workers on the other hand, may not have as much of technical background, and as such can better understand information when it is provided to them in the form of something they are more familiar with, i.e. the energy it takes to power a light bulb or a laptop.

Figure 5.5a and 5.5b: Overall preference for how occupants would like to receive energy information (5.5a - Left) and breakdown of occupant preferences by their occupation Type (5.5b – right).

Referring to Figure 5.5a, the most popular means preferred by respondents for receiving energy conservation information is in the form of a percent reduction compared to previous consumption, except for those in business and administration. The most popular means for receiving energy conservation information for respondents with an occupation in business and administration (at 47% of respondents) was as an analogous amount, compared to only 19% in engineering and 30% in other occupations.

5.3.7. Expectations for a Smart Building

When creating a smart home energy system with occupant in-the-loop controls, a lot of the work that goes into making it possible is in essence also creating a smart building.

One of the objectives for this area of the research study is to get a better understanding of what occupants feel defines a smart building to see if future work done in this space could better meet occupant expectations. 66% of participants felt that a smart building should automatically control building systems (heating, cooling, lighting, etc.) and operate them more efficiently so occupants do not have to worry about them. This was the most popular definition of a smart building amongst participants, and the most popular amongst Engineers as well, with 70% stating this as their number one definition of a smart building. The second most popular definition of a smart building is that they are environmentally sustainable. 40% of participants felt this way, and thought that a smart building should be energy and water efficient and produce less waste than a normal building. This was tied as the most popular amongst those in business and administration, with 57% of participants with this occupational background feeling that this was the best description of smart building. Only 26% of engineers felt that this was the best description of a smart building. Figure 5.6 provides a breakdown of the different Smart building descriptions presented to occupants and the percent of participants that felt each of these descriptions best defined a smart building.

Figure 5.6: What occupants feel best describes a smart building. Each column represents the percent of study participants from different occupation backgrounds that feel a particular description best defines a smart building.

5.3.8. Desired Information to Receive About Energy Consumption

Knowing whether occupants are interested in receiving certain types of information allows for better understanding which information needs to be collected and provided to them to promote efficient energy behaviour. Across all participants there was very positive feedback in terms of their interest in receiving certain types of information to help them in better understanding their home energy systems and reducing their energy consumption.

54% of participants agreed and 28% somewhat agreed that knowing that devices or systems (such as heating, cooling, etc.) are working and fulfilling the required task once they have been turned on, would be something they would like to know. Only 7% of participants disagreed.

90% of participants were in some sort of agreement on the fact that customized suggestions for ways of conserving energy in their home would help them reduce their energy consumption, with only 3% in disagreement.

The type of information that participants were strongest in agreement on in terms of its benefit towards helping them to conserve energy, was knowing how much energy each system, appliance and electronic device in their home was consuming. 72% of participants were in agreement that it would help them reduce their energy consumption with another 21% in somewhat of agreement. Only about 2% of people felt that this would not help them conserve energy. Figures 5.7a, 5.7b, and 5.7c provide a graphical representation of these results discussed.

Figures 5.7a, 5.7b, and 5.7c: Survey participants agreement on the benefit of various pieces of information in helping them reduce energy consumption.

Knowing that systems or devices in your home are working and fulfilling the required task once they have been turned on, would be something I'd like to know (5.7a - left); Having customized suggestions for ways of conserving energy in my home would help me reduce my home energy consumption (5.7b - middle); Knowing how much energy each system, appliance, and electronic device in my home is consuming would help me reduce my energy consumption (5.7c - right).

Figures 5.7a, 5.7b, and 5.7c, show that high percent of people see benefit in the information outlined here to help them in reducing their energy consumption and better understanding their home energy systems. However when asked the question: “what information about home energy consumption is most important to you”, 56% of respondents feel that being provided information regarding the largest energy consumers in their home on a daily basis, is the most important to allow them to be in a better

position to reduce their home energy consumption. Second to that, 26% of participants felt real-time energy information was the most important, and third being customized tips for reducing energy consumption, with 20% of participants feeling that this is one of the most important pieces of information that they could receive to help reduce their energy consumption. As one might expect, total daily and weekly energy consumption is less helpful to occupants as it does not provide any information on where occupants might look to reduce energy consumption. The other three types of information do however provide this, and are not surprisingly more popular. Figure 5.8 provides a breakdown of which types of information people feel will provide the most benefit in helping them to reduce their energy consumption.

Figure 5.8: What information about home energy consumption is most important to occupants. Presented as the percent of occupants that feel that a particular piece of information is the most important in helping them reduce their home energy consumption.

Some of the reasons people may find receiving information on the largest energy consumers in their home so important is because: 1) it simple to understand and does not require them to look at all the electronics and appliances in their home, cutting down on

their own analysis time to figure out what items are consuming the most energy, and 2) they think that by knowing what the biggest energy consumers are within their home will allow them to realize the biggest energy saving rewards for their money and time.

5.3.9. Preferred Format for Receiving Information

The way energy information is formatted and presented to occupants is arguably just as important as the type of information presented to occupants, which was addressed in the previous section. This formatting of information includes everything from the type of device it is presented on, to the accessibility of information and how it is displayed.

Results show that 73% of respondents preferred their energy consumption information to be provided to them through a smart phone application, with the remaining 27% preferring a wall mounted display. Breaking this down by age group, 85% of millennials (ages 18-34) prefer a smart phone application compared to 75% of those aged 35 years or more. Regardless of this difference of 10 percentage points, the overall preference seems to be towards a smart phone application. Figures 5.9a and 5.9b show the results of participants display type preference.

Figures 5.9a and 5.9b: Information display type preference, of all participants (5.9a - left) and by age group (5.9b - right)

When presented with the options of receiving energy consumption and savings through either graphics, charts, or text, the vast majority of occupants (82%) preferred seeing their data through a chart. This provides a starting point for some of the key features to be included in the smart home energy system dashboard for presenting information to occupants about their smart home energy system.

The kind of metrics occupants would like to see their data presented in was the last section included in the study. Out of the five options provided to them, which included; energy saved, dollars saved, tons of CO₂ eliminated, number of cars taken off the road, and equivalent number of trees planted, participants were asked to select which metrics they would most prefer to see their energy conservation displayed in. Surprisingly, commonly used analogies by businesses to provide people with a concept of their energy usage or CO₂ emissions, were the least preferred by respondents. The two most popular ways of viewing energy savings are in the form of kWh and dollars, with 44% of participants preferring their energy conservation information provided to them in kWh as one of their top metrics and 55% of participants preferring their energy conservation information displayed to them in dollars (\$). Of the remaining three metrics, participants ranked: “Tons of CO₂” as their third most preferred metric, “number of cars taken off the road” fourth, and “equivalent number of trees planted” as fifth.

Diving deeper into the energy and dollar metrics, it is interesting to note that those who work in business and administration greatly favoured seeing their energy savings in dollars (\$), with 80% of them stating dollars as their top metric and only 20% stating kWh. Figure 5.10 shows the breakdown of the different metrics and how much of the overall participant group, as well as occupational subsets, preferred them for viewing their energy consumption.

Figure 5.10: Breakdown of the different metrics and how much of the overall participant group, as well as occupational subsets, preferred them for viewing their energy consumption.

5.3.10. Perceived Value of Smart Home System to Occupants

With all the sensors, controls, software development, and installation required for a smart home energy system, there is ultimately a financial cost associated with it. This was addressed in the last section of this study to get an idea of how much extra people might be willing to pay for a home that had a smart home energy system installed in it. Results showed that only 16% of participants stated they would not pay any extra. Of the remaining respondents, 36% said they would pay \$500 extra and 42% stated they would pay between \$1000 to \$2000 extra for a home with a smart energy system. What's encouraging about these results is not only that 84% of participants would pay extra for a smart home energy system, but that close to 50% of them would pay \$1000 or more extra for a home that contained this system. This provides confidence that there is not only interest in smart home systems but that people place monetary value on it. Figure 5.11a provides a breakdown of the amount that people would pay.

For participants that said they would not pay any extra money (\$0) for a home with a smart energy system, the largest percent of those individuals came from the older age groups as opposed to the younger age groups. Figure 5.11b shows what age groups represent the largest percent of those that would not pay anything extra for a home with a smart energy system.

Figure 5.11a and 5.11b: How much extra people would pay for a home with a smart energy system (5.11a – left), what percent of the study population from various age groups would pay \$0 (5.11b – right)

5.4. Conclusion

At the onset of this occupant study/survey aimed at home and apartment owners/renters our goal was to develop an understanding of the best ways to engage residential building occupants to take action towards reducing their energy consumption in their home/unit apartment (dwelling). This required answers to the following questions:

- A. What are the biggest motivators for occupants to take action in becoming more sustainable (reducing their energy consumption, reducing their water use, reducing waste generation, etc.)?
- B. How can energy consumption feedback be formatted to make it easier for occupants to understand, while also being informative and engaging?

Based on the results of this study a relatively even split can be seen between those that are motivated by money to reduce energy consumption and those that are motivated by health and environmental consequences. When digging deeper into how different occupant and household characteristics might correlate to various results, those aged 25-34 cared more about cost than any other age group, with 60% of this population stating cost as their motivating factor and only 43% in most other age groups. It was also found that renters seemed to be more highly motivated by cost than owners, with 60% of renters and only 47% of owners choosing cost as their primary motivator for reducing energy consumption. However, this finding might also be a result of age, as 70% of renters were under the age of 35. These results indicate that there could be a need to have the option of displaying information to occupants in terms of both monetary value as well as health/environmental value.

With gamification and competition as other effective ways of motivating people to take action, this study explored what occupant's preferences were regarding elements of their energy usage that could be used to feed into a potential competition/gamification type format. The first element examined was how occupants would like to view their home energy consumption and whether they would find it most interesting to see it compared to their own average consumption or their neighbors. It was found that 85% of participants were interested in viewing their neighbor's energy consumption against their own. This provides good indication that this type of comparison could be used in the format of a competition or gamification to help instill occupant action. To do this type of comparison as well create a more exciting competitive/gamification program around occupant energy use, there also needs to be timely information collected by the system. In asking occupants whether having real-time energy consumption information would be more

useful to them than monthly bills in reducing energy consumption, 85% were either in complete or somewhat agreement. The positive results from both of these questions, provide confidence that these, and other similar elements, can be used to create gamification/competitive formatting for displaying information and motivating occupants to take action.

When it came to occupant understanding of energy consumption, occupants were asked what type of energy conservation information would be easiest and most intuitive for them to understand. Results showed that the largest percentage of participants (50%) felt that receiving their energy conservation information as a percent reduction from their daily usage would be easiest for them to understand. 30% thought having their energy conservation information presented as an analogous amount (i.e. energy to power X number of lightbulbs) would be easiest for them to understand, and approximately 20% felt receiving their energy conservation information in kWh of energy reduced would be easiest to understand. When analyzing these results in terms of occupation type, 50% of those in business prefer the analogous presentation of energy information, compared to only 19% in engineering and technology, and 30% in other occupations. Not surprisingly those with a background of engineering and technology had the highest percent of participants that preferred viewing energy conservation information in terms of kWh at 27%, however still low compared to the 53% that preferred seeing it as a percent reduction. Based on these results, if only one option was to be provided to occupants for viewing their energy conservation information, it would be as a % reduction. However, if trying to cater to different occupational backgrounds it might be wise to look at providing energy information in terms of an analogous amount to those with a business/administration background.

When analyzing what type of information occupants would prefer to see most in terms of its ability to help them reduce their energy consumption, 56% of participants stated information on the largest energy consumers in their home on a daily and monthly basis would be most beneficial. Only 20% of participants stated receiving customized tips for how to reduce their energy consumption as most helpful to them. This shows that occupants may very well be most interested in knowing where they need to look to reduce energy and feel they that they do not require specific recommendations for what they need to do. Couple this with that fact that 95% of participants agreed with the statement that: “knowing how much energy each system, appliance, and electronic device in my home is consuming would help me reduce my energy consumption”, there is a trend that shows occupants feel they can address energy conservation without conservation tips, they just need to be provided with a better breakdown of how their energy is being consumed within their home. It should also be noted here that total weekly and even daily energy consumption were ranked lowest by participants in terms of its effectiveness in helping them reduce their energy consumption.

The last piece to answering question 2, was figuring out how best to display information to occupants. 73% preferred a smartphone application as opposed to a wall mounted screen to view their energy conservation information on. In terms of format, occupants were presented with three ways for seeing their information; chart, graphic (pictures of equivalent number of lightbulbs), or text and asked which one made it easiest to visualize their energy information. An overwhelming majority (83%) preferred to see their data presented in the form of a chart. Finally, when analyzing what metrics occupants felt were most meaningful in terms of conveying how much energy they had conserved, the dollar metric reigned supreme, with 55% of participants stating they felt this should be the top

metric presented. 44% of occupants selected kWh as a top metric that they would like to see their energy information in. When broken down by occupation, more than 80% of those in business and administration had selected dollars as their number one metric, compared to 50% in engineering and 42% from other occupations. With dollars (\$) and kWh representing the top two metrics as picked by participants, it might be necessary to have both of these presented together to occupants. By using knowledge of occupational background, it is possible to highlight one metric more than the another (dollars for business professionals for example).

The fact that 84% of participants were willing to pay extra for a home that had a smart home energy system, gives increased confidence that occupants would value having this kind of system in their home. respondents also stated that their top two definitions for what they believed a smart building should be, were: 1) automated to control building operations and 2) environmentally sustainable. With the smart home energy system intending to meet both of these definitions, it is well positioned to meet occupant expectations.

Survey bias was mitigated as much as possible by soliciting responses outside of the researcher's friends and family circle, from individuals with little to no personal connection. There were biases in terms of participant occupation types, with 50% having an occupation in the field of engineering and technology, and 25% in the field of business and administration. However this was used as an advantage to understand how occupation types effect occupant preferences and motivations.

The result and analysis of this 125 respondent survey help to form the foundation of the key elements of our smart home energy system so that it is successful in meeting occupant preferences and motivating action towards more sustainable energy behaviour.

5.5. References

- [1] Hollingworth, C., and Barker, L. “Three Behavioral Insights into the Aging Mind.” *Behavioral Economics*. Internet: https://www.behavioraleconomics.com/three-behavioral-insights-into-the-ageing-mind/#_ftn4 , 2015.
- [2] Egan, T. “The Eight-Second Attention Span.” *The New York Times*. Internet: <https://www.nytimes.com/2016/01/22/opinion/the-eight-second-attention-span.html> January, 2016.
- [3] Shin, L. “10 Steps to Conquering Information Overload. Forbes / Personal Finance.” Internet: <https://www.forbes.com/sites/laurashin/2014/11/14/10-steps-to-conquering-information-overload/#1db658927b08> , November, 2014.
- [4] Statistics Canada. “Dwellings in Canada.” Internet: <http://www12.statcan.gc.ca/census-recensement/2016/as-sa/98-200-x/2016005/98-200-x2016005-eng.cfm> , May 2017.
- [5] Statistics Canada. “Condominium Dwellings in Canada.” Internet: http://www12.statcan.gc.ca/nhs-enm/2011/as-sa/99-014-x/99-014-x2011003_1-eng.cfm , 2016.
- [6] Statistics Canada. “Private Households (2011 census).” Internet: <https://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/famil55c-eng.htm> , 2011.
- [7] Franken, R., and Brown, D. “Why do people like competition? The motivation for winning, putting forth effort, improving one's performance, performing well, being instrumental, and expressing forceful/aggressive behavior." *Personality and Individual Differences*. Vol. 19. pp 175 – 184. August, 1995.
- [8] Van Der Linden, S. “The Psychology of Competition: How competitions can lead you to do the right thing for the wrong reasons.” *Psychology Today*. Internet: <https://www.psychologytoday.com/us/blog/socially-relevant/201506/the-psychology-competition> , June 2015.

6. Occupant in-the-Loop Smart Home Energy System Design

6.1. Introduction

Occupant in-the-loop controls often evoke thoughts of a dashboard that provides information to occupants, allowing them to receive information or take a certain action. In the case of a smart home energy system, this information pertains to building systems and energy consumption. Feedback displays help engage occupants to take desired actions and create behaviour change, and has been used successfully in various industries to date. Take for example the car industry and the introduction of hybrid electric cars. Hybrid electric and electric vehicles took the car energy dashboard to another level, providing drivers with real-time indicators as to their driving efficiency levels, the type of energy they are using, and their energy consumption level. This allowed drivers to see real-time information about how they are using their vehicle and motivate them to improve their driving efficiency.

The goal of a smart home energy system with occupant in-the-loop controls is to motivate occupants to change their behaviour by taking actions to become more energy efficient. This is similar to what has been accomplished by hybrid and electric vehicle dashboards, but instead of having a user ease their foot up on the gas pedal, the smart home energy system will motivate occupants to ease up their consumption of household energy use. However, a fancy dashboard alone will not be enough to motivate occupant behaviour change, and the desired outcomes being sought after require multiple steps of research and development to create an engaging dashboard.

This smart home energy system with occupant in-the-loop controls started with a simulation based assessment of occupant impacts on home energy systems and the identification and simulation of occupant faults in Chapters 3 and 4. This provided information as to the household energy systems that need to be addressed with the highest priority by the smart system from a metering and control standpoint, but also from an occupant engagement standpoint. Chapters 3 and 4 helped inform the creation of the study on occupant interaction with household energy systems, which had 125 participants. This step in the design process helped to provide a better understanding of how occupants think about their home energy systems, what they are most interested in, and what motivates their behaviour. The study in Chapter 5 provides the information necessary to design the front end of the system (the user interface or occupant control point) that engages and motivates users to take action. This chapter (Chapter 6) walks through the design and development of the back-end and front-end of the occupant in-the-loop smart home energy system informed by the research in Chapters 3, 4, and 5. This research provides increased confidence that this system will successfully decrease home energy consumption and increase levels of energy efficient behaviour amongst occupants.

6.2. Methodology

Taking a strategic approach to developing this smart home energy system with occupant in-the-loop controls required the two steps mentioned in the introduction section of this chapter. Each step helped to inform the next, eliminating as much guess work as possible and basing all design and development actions on qualitative and quantitative data. This methodology section outlines the process taken to design the metering and control resolution of the system which resulted in the final back-end and front-end system (user

interface and logic flow) design. Figure 6.1 helps visualize the steps leading up to this design phase.

Figure 6.1: Strategic process for developing the occupant in-the-loop smart home energy system

This section provides the details of the occupant engagement system development, which involved determining the recommended metering and control resolution to achieve the highly obtainable energy savings available through occupant engagement as well as help prevent unnecessary energy use through occupant faults. What follows is the methodology for designing the back-end of the occupant engagement system, which includes the connectivity of each of the various meters and control points that have been analyzed, along with their benefits and pricing. Four metering and control packages, which include bronze (currently planned for the Zibi development), silver, gold, and platinum, are outlined in this section and designed based on increasing energy savings potential and increased protection against occupant faults. The analysis and methodology behind how each of the different packages was put together is described in this chapter and provides the necessary background to understand why certain meters and controls

should be treated with more priority over others and therefore make up the foundation of every smart home energy system.

6.2.1. Background

To understand what types of meters and control points would be necessary for reducing energy consumption within a residential apartment or condo unit, analysis had to be conducted into what systems and components occupant behaviour had the greatest impact on in terms of energy and water savings. Using findings from Chapters 3 and 4, it was determined that there is energy savings potential in all home energy systems analyzed, which means considering meters and controls that help facilitate occupant engagement and behaviour change in all of these systems. However, cost needed to be taken into consideration when building out this smart home energy system to ensure it would also be affordable. Various packages were created to address this, starting with lowest cost options that addressed the most significant areas for energy savings and finishing with the highest cost option that addressed all areas of energy saving potential. In other words, only the meters and controls that helped facilitate occupant engagement in the areas of most potential for energy savings were implemented into the first packages, with additional meters and controls that facilitated occupant engagement in areas of lesser savings potential, implemented into the more premium packages.

As seen in Figure 4.2 in Chapter 4, heating and cooling energy consumption had the most potential for energy savings between different occupant behaviour extremes, followed by savings from water heating, and then electronic devices. The dryer, dishwasher and then natural ventilation provided the next largest opportunities for energy savings. How this

translated into the types of sensors, meters and control points selected for each package is explained in the following section

Occupants' faults were also considered in the metering and control resolution selection to ensure a more robust design that could mitigate wasted energy associated with these faults. Figure 4.3 in Chapter 4, shows some of the faults that were analyzed and their resulting impact on energy consumption. How occupants use their electronics, plays a big part in their energy consumption. The results showed that if occupants forget to close their window or leave them slightly open for fresh air, there is a significant increase in the heating and cooling energy demand of the HVAC system. The information from the analysis on occupant faults in Chapter 2, provides additional information on the types of sensors and controls and required connectivity that could pose beneficial in reducing wasted energy consumption.

6.2.2. Back-end and Front-end System Requirements and Objectives

With so much of a buildings energy consumption dependent on how occupants behave, it is important that they receive the most accurate and usable information regarding the systems and built environment around them as well as be provided with the ability to take action based on the information they receive. There are many different pieces that go into creating a smart home or building system which provides usable information and instills occupant engagement, with the meters, sensors and controls being the piece that forms the foundation for the rest of the system. The meters, sensors and controls are the backbone (back-end) of this occupant in-the-loop smart home energy system, dictating how much

information is available to occupants to make intelligent decisions, the quality and accuracy of the information provided, and the ease of control occupants have over their energy consumption.

The goal of this smart system, is to engage occupants to reduce their energy usage. With that in mind, two objectives were used for the selection of the meters and controls.

- Objective 1: Implement meters and controls to provide the necessary information, for the most amount of occupant engagement and subsequent energy savings, while staying within a certain price point.
- Objective 2: Introduce meters/sensors and controls together when there are clear synergies for energy savings between the two of them, making their implementation more powerful compared to if they were just implemented by themselves. For example, smart electricity meters and plugs were introduced together in the silver package to provide the necessary information regarding energy use as well as the ability to control energy use at the appliance level.
- Real-time feedback was an additional priority that was kept in mind when selecting meters and control points. This is because it is more effective than after the fact reporting in creating energy efficient occupant behaviour. This was shown by the Amphiro shower meter study which found that real-time water and energy feedback while showering resulted in occupants reducing their energy and water consumption by 23% [30].

Cost was the biggest constraint on this design, but since there was no clear outlined budget provided during the time of determining optimal metering and control resolution

for Windmill Developments, four packages were created to provide both low and high cost options.

For the front end of the system design, it must convey the data and information collected by the back-end of the system in a way that is compelling, engaging, and motivates occupants to take-action. This means designing the logic flow of information processing in a way that ensures only the most relevant information and insights are provided to the user, the information is provided at a frequency that ensures engagement but does not overwhelm the user, and that the most accurate commands possible are sent to the smart system controls. At the interface, it means packaging and formatting this relevant information in a way that is visually appealing and engaging, simple to understand, interesting enough that the user wants to continue to view the insights provided to them by the system, motivating enough that occupants are compelled to act upon the information provided, and ultimately creating a more energy conscious behaviour change in occupants.

Information and insights obtained from the studies performed in Chapters 3, 4, and 5 in conjunction with the back-end design configuration will be referenced throughout to provide the reasoning behind certain front-end design decisions made.

The functionality of the smart home energy system can extend beyond just energy reduction, to home security and safety as well as convenience. However, for the sake of this thesis, the front-end logic flow and interface design will focus mainly on reducing home energy consumption.

6.2.3. Overview of Meters and Controls

The following meters and control solutions were identified as being able to facilitate the necessary occupant engagement and energy savings investigated in Chapters 3, 4, and 5.

Table 6.1 below provides a summary of the various meters and control points and identifies which have been included in the various smart home packages outlined in Section 6.2.1.5. Figure 6.2 depicts what sensors and control points connect to and benefit what building systems and functions. A more in-depth description as to each sensor and control points function and benefits is provided after Table 6.1 and Figure 6.2.

Table 6.1: Metering and control packages

Meter and Control Type	Data Type	Cost	Br.	Si.	Go.	Pl.
Thermal Energy Meter 1	Measures energy consumption of unit heating/cooling system.	QMC Meters \$450 [1]	X	X	X	X
Thermal Energy Meter 2	Measures energy consumption of DHW system.	QMC Meters \$150 [1]	X	X	X	X
Unit Level Electricity Meter	Measures aggregate electricity consumption of each unit.	QMC Meters \$250-\$300 [1]	X			
Smart Electricity Meter	Measures real-time electricity consumption of appliances and electronics.	Sense - \$300 [2]		X	X	X
Programmable Thermostat	Basic thermostat which sounds like what would be part of the currently planned package.	Honeywell [3] \$70-\$120	X	X		
Smart Outlets	Measure electricity consumption of electronics and wirelessly control them.	Wemo - \$40 [4]		X (1)	X (2)	X (5)
Smart Lighting	Wirelessly control, automate, and schedule lighting.	Phillips Hue [5] starting at \$25/bulb [6]				X

Smart Vents	Vents use motion and proximity sensors to detect which rooms are in use and automatically opens and closes to redirect air as needed. Save 30% on Energy [7].	KEEN [33] Bridge - \$40 Vent - \$100 [7]				
Amphiro Shower Meter	Proven to provide energy savings of 23% on showering [8].	Amphiro - \$100 [9]		X	X	X
Smart Thermostat	Smart thermostats have activity sensors that allow for self-learning and automatic programming of temperature set-points when occupants leave their home [12].	Nest - \$250 [10] Ecobee - \$220 [11]			X	X
Door & Window Contact Sensor	Provides notification of doors and windows being opened or closed.	Samsung \$20 [14]			X	X
Smart Appliances	Connects to smartphone through application and allows control of appliance as well as energy use tracking.	Whirlpool Washer/Dryer - \$1400 Each [15]				
Motion Sensors	Phillips Hue: The Phillips Hue sensors work with the Phillips lighting system. includes daylight sensor.	Phillips Hue - \$39 [16]				X
Daylight Sensor	Natural light sensing and indoor light control. Monitors natural daylight from windows and signals the lighting control system to raise or lower the lights.	Phillips Hue - \$39 [16]				
Outdoor Temperature Sensor	Provides real-time temperature information. The smart system can then use this information to determine whether natural cooling is available and should be used by occupants.	Samsung - \$20 [14]			X	X

Figure 6.2: Meters/controls and their connection with building systems

Thermal Energy Meter 1

This thermal energy meter is used to determine the amount of energy being consumed by occupants for heating and cooling their unit. This is achieved through the measurement of temperature and flow rate of the incoming heating/cooling fluid. Measured data is then pushed to the central hub for use in the occupant engagement/user experience platform. A quote on pricing for regulatory compliant meters was provided by [QMC Meters](#) for \$450/meter [1]. The information provided by this meter helps engage occupants to choose more efficient temperature set-points and use heating setbacks and cooling setups. In conjunction with programmable or smart thermostats, savings on heating and cooling can range from 20-25% (see Appendix A for calculations) [17].

Thermal Energy Meter 2

This thermal energy meter is used to determine the amount of energy being used by occupants for hot water heating. This is achieved through the measurement of temperature and flow rate of the incoming hot water. Measured data is then pushed to the central hub for use in the occupant engagement/user experience platform. A quote on pricing for regulatory compliant meters was provided by [QMC Meters](#) for \$150/meter [1]. The information provided by this meter helps to engage occupants to use water more efficiently, such as not letting the water run when brushing teeth which has been shown to reduce water consumption by 4400 to 6400 gallons per year in a condo unit (assuming 2 occupants). See Appendix A for calculations.

Hydro Ottawa Unit Level Electricity Meter

This meter is used to determine how much total electricity is being used by occupants in their apartments. This does not show how each unit's electricity use is broken down, but does provide real-time electricity use information to occupants. Measured electricity consumption data would then be pushed to the occupant engagement platform for display. A quote on pricing for regulatory compliant meters was provided by [QMC Meters](#) for \$250/meter [1].

Based on a Hydro One study in which 500 customers were provided with real-time electricity consumption feedback displays in their homes, 60% of participants felt the monitor made a difference in their home, while 63% of them expressed that the monitor helped them conserve energy [13]. This same study found a 6.5% reduction in household electricity consumption after implementation of real-time electricity consumption feedback to occupants [13].

Smart Electricity Meter

The smart electricity meter is different from the Hydro Ottawa electricity meter in that it measures real-time electricity consumption of individual appliances and electronics within each unit and not just their aggregate values. The smart electricity meter provides insights into which appliances, electronics, etc. are consuming the most energy on a daily and monthly basis, so actions can be taken to curb their consumption. It can also inform occupants of which devices have been left on and through smart plugs, occupants can remotely turn them off. The smart electricity meter can be plugged right into the unit electrical panel or outlet and monitors the main electricity lines coming into the unit. The cost of this meter is \$300 [2].

The Hydro One study mentioned earlier, estimated that a 10% reduction in household electricity consumption could be achieved with more in-depth feedback on electricity consumption and recommendations for conservation [13]. Other studies have shown up to 12% savings in electricity consumption with real-time appliance level energy consumption feedback [18].

Smart Outlets

In their most basic form, smart plugs offer a means of controlling the power to any electronic or appliance plugged into an electrical receptacle. By doing so it allows occupants to turn off the flow of electricity to electronics/appliances when they are not in use to reduce phantom loads within their home. Since smart plugs wirelessly connect with an occupants smart phone, they can turn on/off their appliances/electronics. This is a powerful and convenient way for occupants to reduce electricity consumption within their house, without any sacrifice to their daily routine. It can also act as a security feature by

allowing occupants to remotely turn on and off their lights while away to make it look like they are home. [Wemo](#) is a popular brand of smart plugs retailing for \$30 [4].

Smart Lighting

Smart lighting allows occupants to wirelessly control and schedule their home lighting. A smart home lighting system can be set on a schedule to turn off at certain times of the day (for example at night when everyone has gone to sleep or during the day when occupants are away at work or school). When synced with a smart thermostat, the lighting can follow its automatic smart scheduling and turn lights on and off without input requirement from the occupant. The Phillips brand of smart lighting allows occupants to add up to 50 lights, switches, etc. to their system bridge and sync them with music, media, Apple Homekit, Nest Thermostat, etc. [5]. A single [Phillips Hue](#) bulb is \$25 [6]. Benefits of smart lighting systems come when occupants have their light put on a schedule to eliminate the potential faults of leaving lights on or have them synced to a Nest thermostat or motion sensor which can automatically turn lights on and off without the need for occupant interaction. The potential fault energy consumption avoided by virtue of this can be up to 100 kWh/year.

Smart Vents

Smart vents use motion and proximity sensors to detect which rooms are in use, residents set room-by-room target temperatures, and motorized vents automatically open and close to redirect air as needed. Room-by-room zoning can reduce energy usage and costs by up to 30% [7]. The smart vents connect to their bridge and then smart phone app for wireless and remote control of room by room heating and cooling. The downside with this smart

device is that it only works with air based HVAC systems. The most popular provider of this smart vent system is [KEEN](#).

Smart Thermostats

Smart thermostats are different from programmable thermostats in the sense that they learn based on occupant preferences and program themselves to the temperatures they like at certain times of the day. Smart thermostats also have the ability to determine when occupants have left their home, and automatically setback or setup the temperature set-point to conserve energy and avoid heating/cooling an empty house. Occupants can remotely control the temperature set-point from their smart phone as well as receive alerts or warnings. Nest and Ecobee thermostats for example have activity sensors that allow for self-learning and automatic programming of the thermostat during periods of time that occupants leave their homes. Annually, Nest and Ecobee thermostats are able to save consumers an average of 10-12% on heating bills and 15% on cooling bills [12].

Programmable Thermostat

Programmable thermostats provided the control means for occupants to operate their heating and cooling systems at efficient temperature set-points as well to schedule heating setbacks and cooling setups. The thermostat will operate the heating and cooling system only as efficiently as the occupant has programmed it to operate. With that said, programmable thermostats are more dependent on occupant engagement to produce energy savings than smart thermostats. In light of this, energy consumption feedback from the thermal energy meter is more important when a programmable thermostat is in

place, as it will hopefully serve to incentivize occupants to take action. [Honeywell](#) provides programmable thermostats in the range of \$70 - \$120 [3].

Window/Door Contact Sensors

These sensors provide the smart home system with information regarding the opened or closed state of doors and windows. By knowing if doors or windows are open or closed, the smart home system can provide alerts/warnings to users if window opening behaviour is having a detrimental effect on the current heating or cooling efforts of the system. It can also allow the smart home system to block use of mechanical heating, cooling and ventilation as long as windows are open. This type of sensor helps facilitate the optimal use of natural ventilation, HVAC controls, and security (notifications to occupants if they have left windows or doors open).

Motion Sensors

Motion sensors allow for the smart home system to identify when occupants are present in the suite or not. This insight is then able to trigger temperature setbacks and setups automatically, smart lights to be turned on or off automatically, smart vents to open or close automatically, and smart plugs to turn on or off automatically. A motion sensor is a facilitator for other smart systems to perform tasks automatically and with more accuracy. The motion sensor provides increased confidence that energy savings will be obtained, even with limited occupant interaction. [Phillips](#) and [Samsung](#) are both popular brands of residential motion sensors

Daylight Sensors

A daylight sensor monitors natural daylight from windows and signals the lighting control system to increase or decrease the artificial lighting intensity according to natural light fluctuations. When paired with dimmable lights, this helps to reduce energy usage while maintaining a consistent light level for a more efficient and comfortable working or living space. However with each unit having a limited number of lights, and with those lights designed to be LEDs, the savings potential is limited as LED lights are efficient and do not consume much energy as it is. The Phillips Hue motion sensor has daylight sensor capability built right in.

Shower Energy Meter

The shower energy meter measures the energy and water consumption from hot water use while the occupant is showering, and displays this information for occupants in real-time. Having a dedicated energy and water meter right in the shower is critical for obtaining the desired energy savings. It has been shown that feedback after the fact has next to no impact on energy consumption reduction, however when occupants are provided with their consumption data while in the act of showering, energy savings on hot water use are shown to be on average 23% [8]. [Amphiro](#) provides this shower meter for \$100 [8].

Outdoor Temperature Sensor

The outdoor temperature sensor in combination with the indoor temperature sensor provided through the suite thermostat, help facilitate the optimal use of natural cooling. The Samsung contact sensor mentioned earlier also acts as a temperature and humidity sensor [14].

6.2.4. Analysis Considerations

The energy savings values provided in the following section for the four packages are based on the energy modelling of a 100 m² (~1000 ft²) condo unit (full details of the modelling specifications used can be found in Appendix A) as well as on the energy saving results from various building energy use and occupant behaviour studies. It is very likely that actual energy savings results will vary depending on the following factors.

- Number of occupants present in condo unit
- Lifestyle and schedule of the occupants present in the unit
- Type of electronics and appliances installed in the unit
- Size of the unit
- Geographical location of the building
- Orientation of the unit

The analysis done for this thesis was based on the presence of two occupants in the condo unit following a 9-5 work schedule, with the vast majority of the day spent away from their condo unit. These were just a few of the many assumptions, that had to be made when estimating the cost and energy savings from the implementation of the various metering and control packages. Other considerations for estimating metering control package cost and energy savings included; the type, quantity, and efficiency of appliances and electronics present in the units, the set-point temperatures for heating and cooling, the set up and set back temperatures for heating and cooling, and the level of occupant engagement.

What follows in the next section is a breakdown of the various meters and controls that were investigated for implementation. The results section then outlines the back-end control and metering packages that were created and the front-end logic flow and interface that were designed based on the chosen back-end platform.

6.3. Back-end and Front-end System Designs

6.3.1. Back-end System Design - Metering and Control Packages

The following section outlines the four metering and controls packages that have been assembled to provide the smart home energy system with the necessary information to facilitate occupant engagement and energy savings. Four packages were created to represent various tiers of monitoring and control that are possible, with each package increasing in the number of monitoring and control points. The assembly of each package starts with the monitoring and control features that provide the most basic information to facilitate the largest amount of potential energy savings, with other meters and controls added to the more premium packages (gold and platinum) to provide more certainty to achieving the targeted energy savings.

Bronze (Br.) Package

The following package is based on the metering and control systems proposed by the residential building development company that funded and partnered with Carleton University on various elements of this thesis research. Based on a February 2016 report regarding utility submetering solutions for the Zibi development, the base metering and controls configuration has been proposed to contain only the elements described in this report and outlined by the development company management staff in a letter contained

in the report. A snapshot of this letter can be found in Appendix A. The basic overview of the various meters proposed for the Zibi development suites can be seen in Figure 6.3.

Figure 6.3: Metering strategy for Zibi units provided by Scott Bentley in Feb 8th 2016 letter

Table 6.2 below provides details as to the meters and controls that have been proposed so far for implementation in the Zibi development condo units, and make up the bronze package. Table 6.2 breaks down the benefits and cost of each meter and controller as well as the potential energy savings it can provide and the level of occupant engagement required to make use of its information to produce energy savings. Required engagement is labelled as high, medium, or low based on how much effort the occupant must put forth in order to achieve energy savings for the specified sensor or control. The amount of effort is determined based on comparing various technologies that enable similar energy savings and how much occupants must do in order to achieve energy savings using each of the technologies. A ranking of high, medium, and low is then determined for each of the various sensors and controls.

Table 6.2: Bronze packages summary¹

Meters & Controllers Required	Benefits	Energy Savings Potential	Cost	Required Engagement
Thermal Energy Meter 1	Real-time heating and cooling energy use feedback	Feeds into programmable thermostat savings	\$450 [1]	High (H)
Thermal Energy Meter 2	Real-time hot and cold water energy use feedback	Consumption data produced by these meters can lead to reduction ideas, leading to potential savings	\$300 [1] (\$150 each)	High (H)
Unit Level Electricity Meter	Unit level real-time electricity consumption	Electricity: 6.5% of HEC (580 kWh/yr) [10]	\$250 - 300 [1]	High (H)
Programmable Thermostat	Scheduled heating and cooling set-point Scheduled heating and	From heating setback [17]: 10-13% (80 - 100 kWh/yr) ~1% of HEC	\$70-120 [3]	High (H)

	cooling setbacks and setups	From cooling setup [17]: 11% (130 kWh/yr) ~1.4% of HEC		
Total		11%-13% (1000 - 1100 kWh/yr) No occupant fault protection	\$1100-1200**	High*

¹See Appendix A for energy savings calculations

HEC – Household Electrical Consumption

*Represents savings values achievable with high occupant engagement and no measures taken to reduce occupant faults.

**Integration & installation costs not included

Silver (Si.) Package

The silver package varies from the bronze package by replacing the unit level electricity meter with a smart electricity meter that measures the electricity consumption at the electronic and appliance level. Metering and control additions that make up the silver package include one smart plug and a real-time energy and water meter for in the shower. The complete list of meters and controls that are included in the silver package have been marked with an X in the silver (Si.) column in Table 6.1.

In Chapter 3, energy consumption for hot water held the second largest amount of savings from occupant behaviour change in a high-performance MURB, with a 1400 kWh/year difference in energy consumption, and second largest in a conventional MURB. This was substantiated by the next occupant behaviour study in Chapter 4 that showed energy consumption from just shower hot water could increase by 65% between active and passive occupants resulting in 870 kWh of additional energy usage. It was for this reason why our first addition to the silver package was a real-time energy and water meter for residential unit showers. Studies have shown that real-time energy and water consumption feedback when occupants were showering, successfully created behaviour change and resulted in energy and water savings [8, 9]. It is worth noting that energy consumption

feedback after the fact was not successful in producing significant behaviour change [8, 9].

Based on the Chapter 3 study, electronics and appliances held the second highest potential for energy savings from occupant behaviour change for high-performance MURBs and third highest potential in conventional MURBs. However, the silver package was also designed to include a smart energy metering system and a single smart plug. The smart metering system replaces the unit level energy metering system to allow for end use energy metering. This insight allows for the system to identify potential user faults as well as the electronics/appliances which are consuming the most energy. With this specific information, occupants can be provided with customized suggestions for reducing their energy consumption. As outlined in Section 6.2.1.3, studies from Hydro One back up the significance of these recommendations. The smart plug would be used in an area where a cable box, TV, and potentially sound system are all hooked up into one outlet, allowing for the control of multiple electronics through one plug. The smart plug would allow for occupants to easily reduce the phantom loads from these devices. The benefits and value of this sensor package to the occupants of the unit in improving their energy and water consumption efficiency, have been summarized in Table 6.3.

Table 6.3: Silver package summary¹

Meters/Controllers Required	Benefits	Energy Savings Potential	Cost	Required Engagement
Thermal Energy Meter 1	Real-time heating and cooling energy use feedback	Supports smart thermostat savings but less than with programmable thermostats	\$450 [1]	High (H)
Shower Water/Energy Meter (Amphiro)	Real-time energy and water consumption	Hot Water: 21% (430 kWh/yr, 2245 gal.) [8, 9] – 4.8% of HEC	\$100 [8]	Medium (M)

	feedback while showering			
Thermal Energy Meter 2	Real-time hot and cold water energy use feedback	Consumption data leads to reduction ideas, leading to potential savings	\$300 [1] (\$150 each)	High (H)
Appliance Level Electricity Meter	Real-time electricity consumption at the appliance and electronic level	Appliances and Electronics: 10-12% of HEC (1000 kWh/yr) [13, 18]	\$250 - 300 [2]	Medium (M)
Smart Plug (1)	Automating and scheduling power outlets	Electricity: 2.6% of HEC (236 kWh/yr) [19]	\$30 [4]	Low (L)
Programmable Thermostat	Scheduled heating and cooling set-point	Heating and cooling: 3.8% of HEC (340 kWh/yr) [20, 29]	\$70 - 120 [3]	High (H)
	Scheduled heating a cooling setbacks and setups	Heating setback [17]: 10-13% (80-100 kWh/yr) ~1% of HEC Cooling setup [17]: 11% (130 kWh/yr) ~1.4% of HEC		High (H)
Total		22% - 24% (2000-2200 kWh/yr) Limited fault protection	\$1200 – 1300**	Medium – High*

¹See Appendix A for Energy Savings Potential Calculations

HEC - Household Electricity Consumption

*Represents savings values achievable with medium to high occupant engagement and limited measures taken to reduce occupant faults.

**Installation and integration costs not included

Gold Package

The gold package utilizes a smart electricity meter that measures the electricity consumption at the electronic and appliance level just like the silver package. Other metering and control additions that make up the gold package include two smart plugs, a

smart thermostat instead of a programmable thermostat, window contact sensors, and a real-time energy and water meter for the shower. The complete list of meters and controls that are included in the gold package have been marked with an X in the gold (Go.) column in Table 6.1. Incremental additions to the gold package are described below. For explanations on the components already present, see the previous packages above.

The programmable thermostat was replaced with a smart thermostat in this package to add another degree of automation to the system and reduce the requirements of occupants to remember to set their temperature set-point to an energy efficient setting. With so much potential for energy savings with temperature set-points, setbacks and setups, the smart thermostat provides some insurance that at least a portion of the potential energy savings will be realized.

In the Chapter 4 analysis on the systems and components within a MURB unit that hold the largest potential for energy and water savings from occupant behaviour change, results showed that natural cooling through window operation provided an opportunity for significant energy savings. It was also found that window operation can be a source of occupant faults, with windows being left open adding to the heating and cooling load of the suite. To mitigate this potential fault from occurring, window sensors were added to the gold package to communicate information regarding open windows with the smart home energy system. This sensor also provides security to the suite as well.

The benefits and value provided by this metering and controls back-end package to the residential occupant in improving their unit energy and water consumption efficiency, have been summarized in Table 6.4.

Table 6.4: Gold package summary¹

Meters/Controllers Required	Benefits	Energy Savings Potential	Cost	Required Engagement
Thermal Energy Meter 1	Real-time heating and cooling energy use feedback	Feeds into smart thermostat savings but to a lesser extent compared to programmable thermostats	\$450 [1]	High (H)
Shower Water/Energy Meter (Amphiro)	Real-time energy and water consumption feedback while showering	Hot water: 21% (430 kWh/yr, 2245 gal.) [8, 9] – 4.8% of HEC	\$100 [8]	Medium (M)
Thermal Energy Meter 2	Real-time hot and cold water energy use feedback	Consumption data leads to reduction ideas, leading to potential savings	\$300 [1] (\$150 each)	High (H)
Appliance Level Electricity Meter	Real-time electricity consumption at the appliance level	Appliances and electronics: 10-12% of HEC (1000 kWh/yr) [13, 18]	\$250-300 [1, 2]	Medium (M)
Smart Plug (x2)	Remote control of power outlets	Electricity: 5% of HEC (440 kWh/yr) [19]	\$60 [4]	Low (L)
Smart Thermostat	Heating and cooling temperature set-point reductions	Heating and Cooling: 3.8% of HEC (340 kWh/yr) [20, 29]	\$250 [3]	High (H)
	Automatic temperature setbacks and setups when occupants leave their suites	<u>Heating</u> : 10% (80 kWh) [10 - 12] ~1% of THEC <u>Cooling</u> : 15% (170 kWh/yr) [10 - 12] ~2% of HEC		Low (L)
Window and Door Sensors	Provide smart HVAC use and notifications when	Prevents occupant faults which could result in up to	\$40 - 60 [14] \$20/sensor	Medium (M)

	windows/doors are left open	500 kWh/yr. of electricity usage [25, 26]		
Total		26% -29% (2300 - 2600 kWh/yr) with additional savings of up to 500 kWh/yr in occupant faults	\$1350 – 1450**	Medium (M)*

¹See Appendix A for Energy Savings Potential Calculations

HEC – Household Electricity Consumption

*Represents savings values achievable with medium occupant engagement and some measures taken to reduce occupant faults.

**Installation and integration costs not included

Platinum Package

The platinum package contains both the thermal energy meters, included in all packages, the smart electricity meter and Ampiro shower meter included in both the silver and gold packages, and smart thermostat and door/window contact sensors as included in the gold package. What sets the platinum package apart from the other packages is the inclusion of motion sensors and smart lighting to increase apartment automation, and five smart plugs to cover most of the appliances and electronics that spend a majority of their time on standby. The complete list of meters and controls that are included in the platinum package have been marked with an X in the platinum (Pl.) column in Table 6.1.

The details of sensors and controls that are also included in other packages have been outlined in the previous packages. This section outlines the new sensors and controls present in the platinum package. The motion sensors allow for items such as smart plugs, lights, and heating and cooling, to automatically act on reducing energy consumption with no (or very limited) occupant involvement. It also allows for better accuracy in sending alerts and warnings to occupants when certain things are detected that seem out of place (abnormal amounts of energy use, windows open, etc.).

The five smart plugs are used for electronics such as the cable box, TV, sound system, coffee maker, and select appliances that are on standby for a vast majority of the day to make cutting power to them when off easier (either done manually through the smart home app, as part of a schedule on the app, or automatically using motion sensors or triggers from the smart thermostat). By using smart plugs with appliances, occupants can than easily reduce their phantom loads through wireless control on their smart phone. With five smart plugs, an increased number of electronics and appliances can be controlled and therefore their phantom load reduced.

Smart lighting systems in conjunction with motion sensors allow for the reduction of occupant faults in leaving lights on. They can be automatically switched on or off, be operated on a schedule or remotely turned on and off by occupants from their smart phone. Smart lighting also provides additional security in making it look like someone is at home by switching lights on and off remotely.

The benefits and value provided by this metering and controls back-end package to the residential occupant in improving their unit energy and water consumption efficiency, have been summarized in Table 6.5.

Table 6.5: Platinum package summary^l

Meters/Controllers Required	Benefits	Energy Savings Potential	Cost	Required Engagement
Thermal Energy Meter 1	Real-time heating and cooling energy use feedback	Feeds into smart thermostat savings but to a lesser extent compared to programmable thermostats	\$450 [1]	High (H)
Shower Water & Energy Meter	Real-time energy and	Hot water: 21% (430 kWh/yr,	\$100 [8]	Medium (M)

	water consumption feedback while showering	2245 gal.) [8, 9] – 4.8% of HEC		
Thermal Energy Meter 2	Real-time hot and cold water energy use feedback	Based on consumption data, provide reduction ideas leading to potential savings	\$300 [1] (\$150 each)	High (H)
Appliance Level Electricity Meter	Real-time electricity consumption at the appliance and electronic level	Appliances and electronics: 10-12% HEC (1000 kWh/yr) [13, 18]	\$250 - 300 [1, 2]	Medium (M)
Smart Plug (x5)	Remote control of power outlets in your home.	Electricity: 6% of HEC (545 kWh/yr) [19]	\$150 [4] (\$30 each)	Low (L)
Smart Thermostat	Heating and cooling temperature set-point reductions Automatic temperature setbacks and setups when occupants leave their suites	Heating and cooling: 3.8% of HEC (340 kWh/yr) [20, 29] Heating: 10% (80 kWh/yr) [10 - 12] ~1% of HEC Cooling: 15% (170 kWh/yr) [10 - 12] ~2% of HEC	\$250 [3]	High (H) Low (L)
Window and Door Sensors	Help provide smart HVAC use and notifications when windows/doors are left open	Prevents occupant faults which could result in up to 500 kWh/yr of additional electricity usage [25 - 26]	\$8-10 [14] \$2.50/sensor	Medium (M)
Motion Sensors	Provides increased automation of	Feeds into savings for smart plugs,	\$40 [16]	Low (L)

	usually occupant dependent tasks	lighting, and thermostat. Prevents occupant faults.		
Smart Lighting	Wirelessly control and scheduling of lighting. Automated when connected to motion sensors.	Potential for savings of up to 100's of kWh/yr in occupant faults. [25, 26]	\$25 each [6]	Low (L)
Total		27% - 30% (2400 – 2700 kWh/yr) Protection of up to 600 kWh/yr against occupant faults	\$1600 – 1700**	Low-Medium *

¹See Appendix A for Energy Savings Potential Calculations

HEC – Household Electricity Consumption

*Represents savings values achievable with limited occupant engagement and robust measures taken to reduce occupant faults

**Integration and installation costs not included

6.3.2. Final Back-end Design Decision

The metering and control packages outlined in this thesis are the foundation or back-end of the occupant engagement system and are what will enable the necessary occupant engagement to achieve highly obtainable energy savings. It is important to note, when choosing a package for implementation, that the amount of energy savings per dollar invested in metering and controls hardware, increases significantly after the bronze package. For example, the amount of energy savings for each dollar invested, quadruples between the bronze and gold package. This means that the first \$1000 invested in hardware for the bronze package gets 13% energy savings while the next \$250 or so of hardware investment to get to the gold package, results in 26% energy savings, 4x the energy savings potential per dollar than the first \$1000. Table 6.6 summarizes this

information by package type. Energy savings calculations and methodology are outlined in Appendix A.

Table 6.6: Summary of metering and controls packages

Package Type	Cost	Energy Savings (% of total household electricity consumption)	Cost/% Energy Savings	Required Engagement
Bronze Package	\$1100 - \$1200	11% - 13% (~1050 kWh)	\$88/%	H
Silver Package	\$1200 - \$1300	22% - 24% (~2100 kWh)	\$54/%	M-H
Gold Package	\$1350 - \$1400	26% - 29% (~2500 kWh)	\$50/%	M
Platinum Package	\$1600 - \$1700	27% - 30% (~2550 kWh)	\$58/%	L - M

*See Appendix A for simple payback and energy saving calculations

Based on this analysis, the chosen metering and controls packages for the back-end of the smart home energy system was chosen as a variation of the platinum package. Choosing the platinum package for the back-end design allows for the maximum number of metering and control points to be explored as well as identify which contribute to the largest amount of energy savings in a real application of this system. The cost of this package in terms of cost/% increase in energy savings, is more than the silver and gold packages, however by implementing the platinum package, it will allow for investigating where potential costs can be cut by eliminating unnecessary devices that do not end up providing a reasonable benefit (upon analyzing the results of the system implementation discussed in Chapter 7). The back-end controls offered by the platinum package also ensures protection against occupant faults which will increase its value over other package types and be better quantified following implementation. This package provides enough energy data and controllability to make changing occupant behaviour in the

direction of becoming more efficient, highly feasible given the right front-end platform and communication strategy. The additional energy consumption required to run the sensors and controls associated with the platinum package back-end design is approximately 80 kWh/yr. See Appendix A for calculations. Figure 6.4 depicts the communication flow between the various sensors and controls that make up the back-end of the occupant in-the-loop smart home energy system.

Figure 6.4: Information flow between the cloud and the smart home energy system sensors and controls

The next chapter outlines the front-end design of the user interface which will utilize the data and information collected by the back-end design just discussed.

6.3.3. Front-End System - Logic Flow and Communication Interface Design

This section provides the design details of the logic flow and communication interface that make up the front-end of the occupant in loop smart home energy system. This section brings together the insights obtained from the study discussed in Chapter 5 and

outlines how the data gathered by the back-end of the system discussed in the previous section are utilized and displayed to occupants.

The logic flow as well as communication and display design for the smart system are described for each major energy system that makes up a typical home. The implementation and testing of this system (described in Chapter 7), will use a variation of the smart home energy system described in this chapter to best suit the specific energy systems present in the dwellings that are used for testing.

The logic flow diagrams for the smart home energy system are subdivided by the four energy systems (plug loads, lighting, HVAC, and hot water heating) within the home that they support metering and control for. Based on the meters and controls available through the back-end system design, there are certain types of data and automated control available to the smart home energy system. The flow diagrams were designed to utilize this data and automated control in order to allow the system to fulfill known ways in which energy savings can be achieved in the home. This is done through encouraging occupant action or using automated actions via the control points available to the system.

6.3.3.1. Plug Loads System - Appliances and Electronics

The portion of the system that covers plug loads includes the appliance level energy meter, smart plugs, smart thermostat, motion sensor, and user interface. Figure 6.5 provides an overview of the data flow between the sensors and controls that make up this portion of the system.

Figure 6.5: The data flow between smart home sensors and controls that influence the plug loads system of the house

The motion sensor allows for automating the control of appliances and electricity consumption based on determining whether occupants are likely to be in a space or not. This contribution to automated control of the plug load system helps to reduce the amount of action items sent to occupants, reserving space for requests to the occupant to be made in action areas where automation is not possible. The smart thermostat acts as a sensor in the plug loads system and helps to provide automated control. With built in presence sensors and algorithms that allow it to determine when occupants are home are away, this information can then be used to inform automated decisions as to how plug loads can be reduced. The appliance level electricity meter acts as another sensor in the plug load system, to inform automation where possible but also inform occupant action. By providing real-time as well as daily, monthly, and annual energy consumption information on every electricity consuming electronic and appliance, smart plugs can be automated to turn on/off when certain energy consumption triggers are met by specific appliances or electronics. It also allows for specific electricity consumption information

to be provided to occupants along with customized suggestions for action. This could include information at the end of the day or week as to what the largest electricity consumers are in their home and customized ways for reducing their electricity consumption on these devices and what the estimated savings will be. The smart plugs act mainly as controllers in the plug loads portion of the energy system, turning on and off electronics and appliances as requested. However, they still feed information back into the system as to when an electronic is turned on or off and the duration of time that it has been on. The user interface acts as both a controller and a sensor. A controller in the sense that information from the system is sent from the system to the occupant to engage an occupant action, and a sensor in the sense that the occupant can send information back into the system as to the state of the surrounding environment to engage the smart home energy system to take an action. Using the GPS function of the smart phone, the application/interface can also provide the system with information regarding whether the user has left their home or not, making it easier to know when an occupant is home or away. What follows is a description of the logic flow between the various sensors and controls described above and communications sent to occupants, in order for the smart home energy system to reduce energy consumption under plug loads in various situations.

Fault Detection - Logic Flow of System

To prevent wasted energy, the first area addressed under the plug loads side of the home energy system, is fault detection. The smart home energy system actively searches for unusual runtimes and functionality of electronics and appliances based on previous occupant behaviour and established estimated runtimes built into the system. Normal functionality of electronics and equipment will vary depending on whether an occupant is

determined to be home or away. For example, the TV on can be considered normal when occupants are home and not normal when occupants are away. The smart plugs are used to turn off appliances if the system determines this as an appropriate action. A subsequent notification of the action taken by the system is either sent immediately to the occupant or stored for them to see when they open up the application. Figure 6.6 provides a flow diagram of the logic behind addressing occupant faults in plug loads. This system also allows for improving home safety by notifying occupants if they have left their oven or hair straightener on for example.

Figure 6.6: Logic flow of system for fault detection in plug loads

Phantom Load Reduction - Logic Flow of System

Phantom load is energy consumption by appliances and electronics while they are turned off. To eliminate a phantom load, the device must be completely cut off from the source of energy. The smart home system accomplishes this by first identifying when electronics or appliances have been turned off. Once turned off, the system determines the state of the occupied space and based on this will use the smart outlets to either cut off power to

the device right away or after a specified amount of time. Figure 6.7 provides a flow diagram of the logic behind addressing occupant faults in plug loads.

Figure 6.7: Logic flow of system for phantom load reduction in plug loads system

Technological and Behavioural Energy Efficiency Improvements – Logic Flow

In conjunction with the automated functions outlined above that the smart home energy system performs to reduce energy consumption, the system strives to engage occupants to take action in order to improve the operational efficiency of electronics and appliances.

The key insights from the Chapter 5 study summarized in Figure 6.8 are utilized for being able to design the system to identify the most relevant and engaging information and present it in a way that motivates occupant action.

- (1) 73% of occupants strongly prefer to connect with their smart home energy system through a smart phone application over a wall mounted display
- (2) 50% of occupants are motivated by cost savings to reduce energy consumption and the other 50% by environmental and human health
- (3) 63% of occupants strongly prefer real-time information on energy consumption as opposed to after the fact reporting (monthly bills)
- (4) Most occupants prefer to receive energy conservation information as a percent reduction compared to previous consumption level.
- (5) The top two things occupants expect from a smart building are that it promotes environmental sustainability and has some degree of automation.
- (6) kWh and \$ are the top two metrics preferred by occupants for viewing their energy consumption information.
- (7) 84% of occupants would like to see how their energy consumption compares to their neighbours,
- (8) 73% of occupants strongly agree that knowing the largest energy consumers in their home will help them to reduce energy consumption.
- (9) 60% of occupants strongly agree customized suggestions for ways of reducing energy consumption in their home will help them to reduce energy consumption

Figure 6.8: Key insights from “occupant interaction with home energy systems” study to inform front-end design of system

Based on the last two insights (8 and 9) in Figure 6.8, the system is designed to provide occupants with a notification at the end of every day as to what the top energy consumers in their home are, as well as customized suggestions on how to reduce their energy consumption. The system also analyses the efficiency of devices that may not necessarily be top energy consumer, but are consuming above normal levels of energy. There are three things the system must do: 1) identify the top five highest energy consuming devices in the home each week, 2) identify the devices that are not necessarily high

energy consumers but seem to be running inefficiently, and then 3) provide recommendations as to how the occupant can reduce their energy consumption. The top five highest energy consuming devices are estimated by the system using the smart energy meter which continuously tracks energy consumption levels of all identified devices on a real-time basis each day. To identify devices that may be running inefficiently, the system starts by analyzing each of their average runtimes, power consumption and estimated monthly and annual energy consumption levels. It then compares these values with values for efficient appliances based on estimates from published sources which include Energy Star and the Federal Government. Depending on where the values for each of these categories fall, will dictate whether the device is running efficiently or inefficiently. Recommendations to users will fall under either operational (behavioural) or technological depending on whether the appliance or electronic has been determined to have above normal length of runtimes/frequency of runtimes or a higher than normal power consumption. The system will provide both operational and technological recommendations for the top five highest energy consuming devices. Estimated savings potential that could result from the implementation of recommendations will also be provided with each recommendation for each device. The savings estimates will be provided in both kWhs and dollars (\$) based on insight 6 in Figure 6.8. Figure 6.9 provides the logic flow for the area of the system explained above.

Figure 6.9: Logic flow of system for identifying inefficient devices and providing savings recommendations

6.3.3.2. Lighting System

The portion of the system that covers lighting includes the motion sensor, smart lighting, smart plugs, smart thermostat, and user interface. Figure 6.10 provides an overview of the data flow between the sensors and controls that make up this portion of the system.

Figure 6.10: The data flow between smart home sensors and controls that influence the lighting system of the house

The motion sensor allows for automating the control of lighting based on determining whether occupants are likely to be in a space or not. This contribution to automated control of the lighting system helps to reduce the amount of action items sent to occupants, reserving space for requests to the occupant to be made in action areas where automation is not possible. The smart thermostat acts as a sensor in the lighting system and helps to provide automated control. With built in presence sensors and algorithms that allow it to determine when occupants are home are away, this information can then be used to inform automated decisions as to when lights that do not have motion sensors connected to them, can be turned off. The appliance level electricity meter as well as smart outlets can inform turn on and turn off actions for the lighting system based on device on or off triggers that occur. They help the system to increase the accuracy of automated actions as well as also inform occupant action if necessary. Regular light bulbs can also be plugged into the smart outlets to give them automated functionality. The smart energy meter tracks the real-time energy consumption of the lighting system to analyze how efficient it is being used compared to average values of the user as well as neighbor usage patterns as well. This allows for specific electricity consumption information to be provided to occupants along with customized suggestions for action. This could include information at the end of the day or week as to what lights have been using the most energy and potential reasons for this. The smart light bulbs that make up the lighting system ultimately control whether light is provided to the space or not, and wirelessly connect to the rest of the sensors and controllers that interface with the lighting system. The user interface acts as both a controller and a sensor in the lighting system. A controller in the sense that information from the system is sent to the user to engage an occupant action, and a sensor in the sense that the occupant can send information back

into the system as to the state of the surrounding environment to engage the smart home energy system to take an action. The smart home energy system is able to use the GPS function of the smart phone to determine when an occupant is home or away. This allows for better control and efficiency of the lighting system.

What follows is a description of the logic flow between the various sensors and controls described above and communications sent to occupants in order for the smart home energy system to reduce lighting energy consumption in various situations.

Fault Detection – Logic Flow of System

Fault detection within the lighting system is achieved similar to electronics and appliances. The system identifies which lights are on at any given time, and based on whether occupants are home or away, turns lights on or off. The system can use multiple sensors to identify whether occupants are home or away, which include the smart thermostats home or away mode, motion sensors, as well as an occupant's cellphone geolocation function. This increased number of sources for identifying the presence of occupants helps to increase the accuracy of automatically turning off lights at the right time. Figure 6.11 shows the logic flow of the system for determining whether an occupant has forgotten to turn the lights off in a room and should then turn lights off using the smart bulbs and smart outlets.

Figure 6.11: Logic flow of system for reducing lighting energy consumption when occupant has left a room

Identifying Energy Efficiency Improvements – Logic Flow of System

In conjunction with fault detection, the system also strives to increase the overall efficiency of the lighting system by using sun light as well as encouraging the implementation of efficient lighting. The daylight sensor built into the motion sensor allows for lights to be automated to be turned on by the motion sensor only if there is not enough lighting provided by the sun. If the lights are not connected to the motion sensor but sufficient lighting is available from the sun, occupants will be sent a notification to use daylighting if they turn on a light switch in a room.

Using the smart energy meter, the efficiency of lights connected to various switches can be determined. By having occupants input the amount of lights connected to a particular switch and using energy consumption information available through the smart energy meter, the system can determine whether efficient (LED) or inefficient (incandescent) lightbulbs are being used by calculating the energy consumption per bulb. Depending on what is determined by the system, a notification will be sent to the occupant to change the lightbulbs connected to a particular switch.

Figure 6.12a (left) and 6.12b (right): Logic flow of system for improving the lighting energy efficiency using daylighting (6.12a) and lighting upgrade recommendations (6.12b)

6.3.3.3. HVAC System

The portion of the system that covers the HVAC system includes the appliance level energy meter, smart plugs, smart thermostat, motion sensor, and user interface. Figure 6.13 provides an overview of the data flow between the sensors and controls that make up this portion of the system.

Figure 6.13: The data flow between smart home sensors and controls that influence the HVAC system of the house

The motion sensor comes with the smart thermostat to help it more accurately determine when occupants are home or away by picking up motion in an additional room to the one

that the smart thermostat is in. The smart thermostat from Ecobee also comes with a built-in motion/presence sensor. This helps the thermostat to automate the setbacks and setups of temperature set-points when occupants leave the home, saving energy on heating and cooling. The smart thermostat acts as both a sensor and controller in the HVAC portion of the smart home energy system, picking up on occupant presence and sending commands to the heating and cooling system as to when to turn on and off. The appliance level electricity meter acts as sensor in the system, measuring the electricity consumption of all heating, cooling, and ventilation sources powered by electricity. This feedback to occupants allows them to better understand how HVAC influences their overall energy consumption and how much it increases their energy demand at any given time of day. An outdoor temperature sensor provides the smart home system with information as to the state of the outdoor air (humidity and temperature) and whether it can be used for natural cooling instead of mechanical cooling. Smart plugs can also have heating, cooling, or ventilation devices plugged into them (fans, heaters, and AC units) which make them sources of energy consumption in conjunction with the central HVAC systems connected to the smart thermostat. The smart plugs can be used to control the functionality of these HVAC devices similar to how the thermostat controls the more central HVAC equipment, reducing occupant faults and wasted energy associated with non-central heating, cooling and ventilation devices being left on when occupants are not home or when they should not be used. The HRV unit has been included as part of this smart home energy system because of its role in automating the use of outdoor air for natural cooling. The HRV fan turns on to provide natural cooling when requested by the thermostat. The thermal energy meter provides another source of measuring energy consumption if the heating and cooling equipment does not solely run on electricity. It

measures the amount of thermal energy flowing through the pipes coming into the dwelling to provide heating or cooling. Based on this information and the type of central heating or cooling system, the smart home energy system can then determine the amount of fuel energy required to provide this thermal energy and convert this to an equivalent kWh. The window contact sensor provides the smart system with information as to the closed or open state of windows in the home. This information can then be used by the thermostat to ensure efficient control of the HVAC system, preventing any heating or cooling from happening when windows are left open. Finally, the user interface acts as both a controller and a sensor. The user will be requested to perform certain actions through the user interface to improve the efficiency of the HVAC system and be encouraged to send information back into the system such as heating and cooling set-points. Using the GPS function of the smart phone, the application/interface can also provide the system with information regarding whether the user(s) has/have left their home or not, providing knowledge on whether an occupant is home or away, and improving the accuracy of automating the control of the HVAC system. What follows is a description of the logic flow between the various sensors and controls described above and communications sent to occupants, in order for the smart home energy system to reduce HVAC energy consumption in various situations.

Fault Detection – Logic Flow of System

The fault detection associated with the HVAC system is to ensure actions taken by occupants that could cause significant amounts of wasted energy consumption, are mitigated. The primary fault that is addressed with the smart home energy system is around windows being left open during times of mechanical heating or cooling requests.

The outdoor temperature sensor, smart thermostat, user interface, window contact sensors, and smart outlets all communicate with one another to ensure this fault is mitigated. When an occupant opens a window, it is usually for two reasons, either to bring fresh outside air inside or to bring cooler outdoor air inside. However, when this is done during times that heating or cooling equipment is also running, or the open windows are forgotten and mechanical cooling turns on, this can cause significant amounts of wasted energy. To help prevent this from happening, the smart home system senses when a window has been opened and adjusts the operation of heating and cooling equipment accordingly. Figure 6.14 provides the logic flow of the systems for mitigating faults associated with windows being left open.

Figure 6.14: Logic flow of system for preventing wasted HVAC energy through open windows

Identifying Energy Efficiency Improvements – Logic Flow of System

To increase the overall energy efficiency of the HVAC system, efficient temperature setups, setbacks and set-points are utilized in conjunction with outdoor air for natural cooling when possible. Setups and setbacks are preprogrammed into the smart system to vary (increase in cooling mode and decrease in heating mode) the temperature set-point by 3°C. These setups and setbacks have been programmed into the system to occur when

the system enters “away mode” (no occupants are home) as well as in the heating season when occupants go to sleep. Preprogrammed set-points of 22°C in the winter and 24°C in the summer are built into the system. When the occupants change these set-points the system will collect information on the energy usage and provide them estimated savings and comparisons for readjusting their temperature set-point to something of higher energy efficiency.

To utilize outdoor air for natural cooling, occupants either have to open windows at the right time to let in cold outdoor air or/and the system can utilize the ERV bypass to automatically bring the outdoor air inside. A temperature sensor on the outside of the home provides the system with the current outdoor temperature, while the thermostat provides the system with the current indoor temperature, the temperature set-point for cooling, and the projected outdoor temperatures for the rest of the day. The smart home energy system uses this information to determine when natural cooling should be utilized and sends communications to the control points of the system to bring in outdoor air.

Estimates of energy savings can also be provided to the occupants in real-time when the natural cooling is used. Figure 6.15 provides the logic flow of the smart home energy system for increasing the energy efficiency of the HVAC portion of the system by using natural cooling. Figure 6.16 provides the logic flow associated with increasing the efficiency of the system using setbacks, setups and energy efficient temperature set-points.

Figure 6.15: Logic flow of system for increasing the energy efficiency of the HVAC portion of the smart home energy system by using natural cooling

Figure 6.16: Logic flow of system for increasing the energy efficiency of the HVAC portion of the smart home energy system by using efficient temperature setbacks, setups, and set-points

6.3.3.4. Hot Water Heating System

The portion of the smart system that covers the hot water heating system includes the appliance level energy meter, shower meter, thermal energy meter and user interface.

Figure 6.17 provides an overview of the data flow between the sensors and controls that make up this portion of the system.

Figure 6.17: The data flow between smart home sensors and controls that influence the hot water heating system of the house

The appliance level electricity meter acts as sensor in the system, measuring the electricity consumption of any equipment that consumes electricity to heat water for the home. It also measures any electricity consumption associated with pumps to move water throughout the home. In homes where the hot water is supplied from a central source, a thermal energy meter measures the energy consumption from hot water use. This information sent to the user interface allows occupants to see what times of the day they are using the most energy for hot water heating, and how large a share of their homes energy consumption it makes up. The shower meter provides real-time information to occupants as to how much energy they are using as they shower to incentivize shorter shower times. What follows is a description of the logic flow between the various sensors and controls described above and communications sent to occupants in order for the smart home energy system to reduce hot water heating energy consumption in various situations.

Identifying Energy Efficiency Improvements – Logic Flow of System

To increase the overall energy efficiency of the hot water heating system, all actions must be taken by occupants. This means that for this part of the system, no actions are automated and the smart home energy system must motivate the occupant with the proper information to perform all desired actions. Figure 6.18 provides the logic flow of the hot water portion of the smart home energy system for reducing hot water usage and energy consumption.

Figure 6.18: Logic flow of system for increasing the energy efficiency of the hot water portion of the smart home energy system by using energy recording, information feedback, and recommendations for conservation

6.3.3.5. Smart Home Energy System Communication Format

The communications presented to the occupant through the user interface were formatted to be as user friendly and as engaging as possible based on the insights provided through the Chapter 5 study on occupant interactions with their home energy system. Summarized in Figure 6.8, the insights inform the communication format design decisions that have

been detailed in this section and the design of the user interface, the home screen of which is depicted in Figure 6.19.

User Interface Hardware and Platform

Starting with the first insight which was that 73% of occupants strongly prefer to connect with their smart home energy system through a smart phone application then a wall mounted display, the user interface would be provided to occupants through a smart phone application downloadable to their phone. The advantages of this design decision are that it reduces the costs of additional hardware and installation required for a wall mounted display and it allows the system to utilize all the functionality already built into a smartphone which include things like GPS and weather applications.

Information Delivered

With so much information and data collected by the smart home energy system on a real-time basis, it is important to understand what specific types of information are most likely to engage occupants to take-action. This eliminates the need to bombard occupants with unnecessary information hoping that some of it resonates with them. This strategy runs the risk of overwhelming the occupant, causing them to shut off notifications from their smart home energy system all together. Touched on here are some of the key pieces of information that will be provided to occupants based on the insights from Chapter 5.

Along with always making real-time energy information on all systems within their home available to occupants, the system will highlight the largest energy consumers in their home so occupants can better focus their efforts on reducing energy consumption. This design decision was based on the insight that 73% of occupants strongly agree that

knowing the largest energy consumers in their home will help them reduce their energy consumption. Customized suggestions for ways of reducing their energy consumption is the second key piece of information provided to occupants based on data collected by the system. 60% of occupants strongly agree, with another 30% in somewhat of agreement that customized suggestions for reducing their energy consumption would help them reduce their energy consumption. These suggestions are customized in the sense that the smart system can identify which systems and devices in the home are consuming the most energy and provide recommendations specific to each one of them. Total energy consumption and system level energy consumption comparisons are another key information type that is provided to occupants in order for them to see how their energy efficiency is progressing against various baselines. These baselines include their own average consumption as well as other neighbours' average consumption. The decision to provide this information is based on the finding that 84% of occupants would like to see how their energy consumption compares to their neighbours. Understanding when systems are on and functioning correctly is an additional piece of information that is provided through the smart system to give occupants peace of mind that systems are working correctly in their home even if they cannot hear or see them doing so.

All of the information provided to occupants in the areas outlined above, not only inform them about how they are consuming energy in their home, but also educate them on energy consumption as well. When certain pieces of information are presented to occupants, both education and a call to action will be included. For example, when occupants receive information that air conditioning was the largest consumer of electricity in the past month, they will also be provided with a statement that says:

“Increasing the setpoint on your thermostat can save you energy on cooling. Set your

thermostat up one degree today and it is estimated you will save x% electricity over the next month.”

Formatting of Information

Not only is the type of information important, but the frequency and formatting is critical as well. This encompasses things like whether certain information should be sent to occupants in real-time, daily or weekly and in what type of units, kWh, dollars, percent, etc., to ensure the highest likelihood of interest and engagement from occupants. Figure 6.19 depicts the different ways that occupants would like to see their energy information displayed. Based on the insights from Chapter 5 summarized in Figure 6.8 earlier in this chapter, information to occupants will be recorded and made available to occupants in real-time, with various key pieces of information sent to them on a daily or weekly basis to make sure occupants are not overwhelmed with information. kWh and \$ will be used as the primary units to communicate energy information to occupants. This is because they are the top two metrics preferred by occupants for viewing their energy information. The use of gamification will be incorporated into the smart home energy system, not only because of the success it has had in motivating occupants to reduce their energy consumption (touched on in the last section of the literature review), but also because of the feedback received by occupants in the Chapter 5 study. The fact that 84% of occupants wanted to see their energy information compared to their neighbours, provides reassurance that occupants would probably welcome the idea of information presented to them in a competition style format. This would work best in a condo or apartment unit where this system is implemented by the development or management company across multiple units allowing for multiple users in close proximity and with similar building

systems. This comparison would include a percent reduction from their own baseline as well their neighbours for any energy savings achieved. This is based on the insight that a majority of occupants prefer to see energy savings presented to them in terms of a percent reduction.

Occupant Expectations of a Smart Home

As concluded from the Chapter 5 survey study, the top two expectations occupants have of a smart home energy system is that it promotes environmental sustainability and has some degree of automation. Based on this insight, energy conservation information from the smart home energy system will be provided to occupants with insights as to how it relates to environmental sustainability, there by addressing occupants expectations. The smart home energy system also has various aspects of automation which have been outlined in the previous sections of this chapter. However, despite the fact that there is automation built into this smart system, one of its primary objectives is to engage occupant action. It is for this reason why so much effort was put into conducting the studies outlined in Chapters 3, 4, and 5, which served to provide a stronger understanding of how best to engage occupants to reduce their energy consumption.

Figure 6.19: Home screen of user interface

6.4. Conclusion

The design of the smart home energy system consisted of both a back-end and front-end system design. Four different control and metering resolution packages were configured based on insights from Chapters 3 and 4 as to the energy impact of occupants on home energy systems. Cost, potential energy savings, degree of occupant engagement required to achieve those energy savings, and simple payback period were then calculated for each configuration so an analysis could be conducted as to which package would be best for the smart home energy system based on which combination of these metrics was most important. The platinum package was ultimately chosen as the controls and metering configuration for the system as it held the highest potential for energy savings along with the most robust controls and sensor options available to test with different connections for

engaging occupant action and achieving the estimated energy savings. A summary of the back-end controls and metering system specifications is provided in Table 6.7 below.

Table 6.7: Specifications for the Platinum Metering and Controls Configuration

Meters and Controls Included	Energy Savings Potential	Cost	Required Engagement
Thermal Energy Meters, Shower Meter, Smart Electricity Meter, Smart Plugs, Smart Thermostat, Window Sensors, Motion Sensors, Smart Lighting	27% - 30% (2400 – 2700 kWh/yr) Protection of up to 600 kWh/yr against occupant faults	\$1600 - \$1700 *integration and installation costs not included	Low-Medium

The front-end system design consisted of two parts, the logic flow and communication formatting. Creating the logic flow for the system required a basic understanding of what typical operations occur within a home (whether that be a detached house or high-rise apartment unit) and how the smart system could best increase energy efficiencies when certain triggers within the home occur. The logic flow of the smart system was organized based on the four different home energy systems, HVAC, hot water heating, lighting, and plug loads, and the logic flows for the various triggers within each system were created. The extent to which certain triggers could be used, actions could be made, and automation could be incorporated into the system, was limited to the sensors and controls available through the back-end design as well as energy systems present within the dwelling. However, as intended, the back-end of the system provided enough sensor and control variations to collect the data necessary to drive the estimated energy savings calculated. The logic flow for each energy system included some degree of automation as well as occupant engagement through energy insights and calls to action.

The second part of the front-end design was the communication formatting of the system, which was based on insights gathered from the survey study outlined in Chapter 6. This study consisted of gathering information on occupant preferences and behaviours in relation to their home energy system and then analyzing them based on various occupant characteristics. These insights were summarized in Figure 6.8 and informed the key elements of the communication of energy information to occupants, mainly: the hardware and platform used for the user interface, the type of information that would be delivered to occupants on a regular basis from each system, the formatting of this information, and the general expectations occupants had from a smart home system. The communication formatting of the system is of a high level of importance as it determines whether the smart home energy system is successful in engaging occupant action towards more energy efficient behaviour or not.

In the next chapter, this smart home energy system is implemented into two different types of residential dwelling types to better understand its energy saving potential as well as gather insights into further smart home system designs.

6.5. References

- [1] Phone call with Mike Easton from QMC Metering Solutions. Based out of Canada (offices in Vancouver, Toronto, Ottawa). <http://qmmeters.com> . 2018.
- [2] Sense. <https://sense.com/buy.html> , 2018.
- [3] The Home Depot. “Wifi Thermostats.” Internet: <http://www.homedepot.com/p/Honeywell-Wi-Fi-Programmable-Touchscreen-Thermostat-and-Free-App-RTH8580WF/203356032> , 2018.
- [4] Belkin. “Wemo Switch Smart Plug.” <http://www.belkin.com/us/p/P-F7C027/> , 2018.
- [5] Philips Hue. “Hue Products.” <http://www2.meethue.com/en-ca/> , 2018.

- [6] Amazon. "Philips Hue White A19 60W Equivalent Dimmable LED Smart Light Bulb Starter Kit." <https://www.amazon.com/Philips-Hue/pages/default?pageId=TOPAYHA49S592D> , 2018.
- [7] KEEN Home. "Smart Vent." Internet: <https://keenhome.io/smart-vent> , 2018.
- [8] Amphiro. "Home." <https://www.amphiro.com/en/> , 2018.
- [9] Amazon. "Amphiro A1 Self Monitoring Water & Energy Smart Meter for Shower." Internet: <https://www.amazon.com/Amphiro-Monitoring-Energy-Shower-amphiro-a1-s004/dp/B00K9QL1C6> , 2018.
- [10] The Home Depot. "Wifi Thermostats." Internet: <http://www.homedepot.com/p/Nest-Learning-Thermostat-3rd-generation-T3007ES/206391087> , 2018.
- [11] Ecobee. "Savings from your Ecobee." Internet: <https://www.ecobee.com/savings/> , 2018
- [12] Nest Labs. "White Paper: Energy Savings from the Nest Learning Thermostat:
- [13] Energy Bill Analysis." Internet: <https://nest.com/downloads/press/documents/energy-savings-white-paper.pdf> , February 2015.
- [14] Mountain, D. "The Impact of Real-Time Feedback on Residential Electricity Consumption: The Hydro One Pilot." Internet: <http://www.reduceenergy.com/PDF/Summary%20Results%20Hydro%20One%20Pilot%20-%20Real-Time%20Feedback.pdf> , March 2006.
- [15] Samsung. "Sensors." Internet: <https://www.samsung.com/us/smart-home/smartthings/sensors/f-mlt-us-2-f-mlt-us-2/> 2018.
- [16] Whirlpool. "8.8 cu.ft. Smart Top Load Electric Dryer with Remote Control." Internet: <https://www.whirlpool.com/laundry/dryers/electric/p.8.8-cu.-ft.-smart-cabrio-large-capacity-dryer-with-laundry-app.wed8700ec.html?==#where-to-buy> , 2018.
- [17] Philips Hue. "Hue Motion Sensor." Internet: <https://www2.meethue.com/en-us/p/hue-motion-sensor/046677473389> ,2018.

- [18] Manning, M., Swinton, M., Szadkowski, J., Ruest, K. “The effects of thermostat set-back and set-up on seasonal energy consumption, surface temperatures and recovery times at the CCHT Twin House Facility.” *NRCC*. pg. 1-12. 2007.
- [19] Stanford University. “The Persistence of Feedback Induced Energy Savings.” Internet: <http://web.stanford.edu/group/peec/cgi-bin/docs/behavior/research/Ehrhardt-Martinez%202011%20-%20Feedback%20and%20Persistence%20Paper.pdf> , 2010.
- [20] Ontario Energy Board. “Defining Ontario’s Typical Electricity Customer.” Internet: https://www.oeb.ca/oeb/Documents/Documents/Report_Defining_Typical_Elec_Customer_20160414.pdf , April 2016.
- [21] Natural Resources Canada. “Survey of Household Energy Use 2011–Detailed Statistical Report.” pg. 95. 2014
- [22] Lawrence Berkley National Laboratory, U.S. Department of Energy, U.S. Environmental Protection Agency, California Energy Commission.” Home Energy Saver and Score: Engineering Documentation.” Internet: <http://hes-documentation.lbl.gov/calculation-methodology/calculation-of-energy-consumption/major-appliances/miscellaneous-equipment-energy-consumption/default-energy-consumption-of-mels> , 2000.
- [23] Natural Resources Canada. “Micro-Hydropower Systems: A Buyers Guide.” Internet: <http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/buyersguidehydroeng.pdf> , pg. 45-46. 2004.
- [24] J.C. Haysom and J.T. Reardon. “*Current Approaches for Mechanical Ventilation of Houses*.” Internet: https://www.nrc-cnrc.gc.ca/ctu-sc/files/doc/ctu-sc/ctu-n15_eng.pdf , 1998.
- [25] Windmill Developments. “Iles.” Internet: <http://www.zibi.ca/wp-content/uploads/2015/05/Iles.pdf>, March 2016.
- [26] ASHRAE. “ASHRAE 90.2-2007.” *Internal heat gain schedule*. Internet: https://ashrae.iwrapper.com/ViewOnline/Standard_90.2-2007 , 2007

- [27] Kohta, U. Joseph, L. "Building Science Corporation: BA-1506: Field Testing of Compartmentalization Methods for Multifamily Construction." Internet: <https://buildingscience.com/documents/bareports/ba-1506-field-testing-compartmentalization-methods-multifamily/view> ,March, 2015.
- [28] L. Rickets and J. Straube. "A Field Study of Airflow in Mid to High-Rise Multi-Unit Residential Buildings." Internet: https://www.ashrae.org/File%20Library/docLib/Public/200583084452_886.pdf ,October, 2014.
- [29] AutoDesk. "Natural Ventilation. " Internet: <https://sustainabilityworkshop.autodesk.com/buildings/natural-ventilation> , 2014.
- [30] Swiss Federal Office of Energy. "ewz-Amphiro Study: The effectiveness of Real-Time Feedback." pp.2. 2014.

7. Smart Home Energy System Prototype Field Testing

7.1. Introduction

Using the smart home energy system design from Chapter 6, a field test was created to test the smart home energy system in order to analyze its practicality, functionality, and benefits for reducing energy consumption. There are other benefits that the system provides such as security, however the focus of this test was on understanding the benefits of this system in reducing home energy consumption. The prototype test consisted of an implementation of the smart home system in two different dwelling types, detached home and condo unit, and an analysis of the benefits and insights provided. The occupants of the dwelling consisted of the author of this thesis and his significant other. The prototype test focused on both similar and different elements of the system in each of the different dwelling types.

The goals of this prototype field test were: 1) to quantify the potential energy savings that could be achieved by the smart home energy system and 2) identify learnings from occupant interaction with the smart home energy system to feed back into improving its design.

7.2. Methodology

The smart home energy system implemented for this prototype test was based on the design in Chapter 6, consisting of as many elements and as much functionality as possible. Funding, time, and availability of certain sensors and controls were the limiting factors to implementing an exact replica of the system in Chapter 6. However, sensors and controls as well as functionality of the smart system pertaining to parts of the home

energy system were able to be tested accept for the hot water system. A large study was conducted for the Swiss Federal Office of Energy (SFOE) that confirmed an average of 430 kWh/home/year of energy savings across 3,000 households for just shower hot water [1]. Their results show the substantial savings that can be achieved and help to substantiate the claims made for the benefits of the hot water energy portion of the smart home energy system without having to implement it as part of this test. Table 7.1 summarizes the sensors and controls from the smart home energy system that were able to be implemented as part of this prototype test.

Table 7.1: Meters and controls implemented as part of smart home energy system prototype test

Meters/Controllers Required	Benefits	Cost
Appliance Level Electricity Meter (Smappee)	Provides real-time electricity consumption information at the appliance and electronic level.	\$300 [2]
Smart Plug (x4)	Provides remote control and monitoring of power outlets.	\$70 [3]
Ecobee Smart Thermostat	Promotes energy efficient use of HVAC system by automatically setting energy efficient temperature setbacks and setups when applicable.	\$250 [4]
Samsung Window and Door Sensor (x2)	Help provide smart HVAC use and notifications when windows/doors are left open.	\$80 [5]
Outdoor Temperature and Humidity Sensor	Provides real-time temperature and humidity values for the air around the home. Helps with operating natural cooling.	Included in window sensor [5]
Philips Motion and Daylight Sensor	Provides automated control of lighting based on motion and daylight.	\$50 [6]
Philips Hue Smart Lighting (x5)	Provides the opportunity to schedule lighting to turn on and off based on various triggers that increase the energy efficiency of the lighting system. Allows it to connect into automatic controllers like motion and daylight sensors.	\$250 [6]
Total		\$1000

7.2.1. Testing Method

Length of testing for the smart home energy system consisted of two months in each dwelling. The only piece of the system that was used for a longer testing period was the Ecobee smart thermostat. It was used for testing in the condo unit (one of the dwelling types) for 3 months in order to quantify the potential for natural cooling during the spring. The length of testing time was enough to assess the smart home energy systems impact on plug loads, however 2 months of testing made it difficult to assess the smart systems impact on the HVAC energy system. This is because the testing period occurred during the spring months of March, April, May and June and heating and cooling energy requirements were already much lower compared to other times of the year. The shorter time period for testing also made it difficult to quantify the lasting impact of certain motivating factors on occupant behaviour. However, valuable qualitative insights were still obtained from the authors experience in this smart home energy system prototype test environment, which are outlined in section 7.3.5 of the results section. Performance of the system was assessed based on the energy savings that were able to be obtained as well as occupant feedback on the usability of the system. One of the key objectives of this prototype testing was to gain occupant feedback as to the systems functionality and ability to engage them to take action. As a result, both good and bad performance characteristics of the system will provide valuable insights for future development work.

7.2.2. Installation

This prototype smart home energy system was tested in two different types of dwellings which included a detached home and a condo unit. The reason for using two different

types of dwellings was to investigate how the smart energy systems results varied given a different dwelling, as well as test scenarios specific to the different dwelling types. Table 7.2 contains the characteristics of each of the dwellings in this test.

Table 7.2: Dwelling characteristics

Specifications	Detached Home	Condo Unit
Floor area	2500 ft ² (232 m ²)	1000 ft ² (93 m ²)
WWR	40%	100%
Heating and cooling systems	Heating: Natural gas boiler Cooling: Electric heat pump	Heating and cooling: 4 Pipe fan coil unit
Number of occupants	2	2
Occupant types	Occupant 1: Employed Occupant 2: Student	Occupant 1: Employed Occupant 2: Employed
Duration of test	2 months	2 months

Smappee Smart Home Energy Meter

Smappee is a smart energy meter that estimates the energy consumption of electronics and appliances within a person's home [2]. In the case of this smart home energy system prototype, it was installed at the electrical panel in each of the dwellings, with two circular clamps (each with a diameter of 2 inches) placed around the two main wires coming into the panel box. The energy meter was then connected to the Internet and smartphone through the Smappee application. Once installed, it started to analyze the different electrical signatures in each of the dwellings as various electronics and appliances were turned on and off. It took about a week to identify some of the dwellings electronics and appliances, and another week after that to identify the remaining majority of electronics and appliances. Once found by Smappee each electronic and appliance had to then be properly identified and labelled. This required turning on and off every electronic and appliance in the dwelling to see which of the devices that Smappee had

found, identified itself as being turned on and off at that moment. Once this was determined, the general appliance or electronic could be specified by the occupant as a fridge, stove, TV, etc. on the Smappee application.

Smart Plugs (x4)

Smart plugs measure the energy consumption of the electronics that are plugged into them as well as can turn on or off the electricity flowing to those devices [3]. With 4 smart plugs acquired for this prototype test, they were installed at locations with a lot of electronics plugged into one outlet as well as locations where an appliance would be sitting idle for a large part of the day. In both dwellings, one smart plug was installed in the home office, one in the kitchen where the coffee maker plugs in, and the other in the living room area. In the detached home the 4th smart plug was installed in a second home office and in the condo unit it was installed in one of the bedrooms that contained a TV and speaker system plugged into a single outlet. Installation involved plugging the smart plugs into a wall outlet, connecting them to the Internet and occupants smartphone via the WEMO application, and then plugging the desired appliances and electronics into it.

Ecobee Smart Thermostat

The Ecobee smart thermostat adds increased automation and intelligence to controlling residential and commercial heating and cooling systems. Unlike a programmable thermostat, the Ecobee can automatically adjust temperature set-points and change the systems mode (cool, heat, auto, or off), based on various triggers that have been setup [4]. The installation of Ecobee thermostats in both locations required the replacement of the old thermostat with the Ecobee thermostat, ensuring that all wires were connected

properly to allow for full system functionality. The Ecobee thermostat was then connected to the Internet as well as the occupants smartphone through the Ecobee smartphone application. The Ecobee monitors various interior and exterior air characteristics and stores them in 5 minute increments for further analysis later.

Samsung Contact and Temperature Sensors

The two sets of contact and temperature sensors that were implemented as part of this smart home energy system prototype provide two purposes: 1) to provide automations and notifications associated with windows being opened or closed, and 2) providing automations and notifications associated with outdoor temperature [5]. One sensor was positioned on a main window used for ventilation, and another placed outside of the dwelling to measure outdoor air temperatures. The two sensors were connected to the Internet via a central hub connected to the dwellings router and then to the occupants smartphone via the Samsung application.

Phillips Smart Light Bulbs (x5)

The smart LED bulbs from Philips called “Philips Hue” can be automatically controlled by various triggers, scheduled by the occupant, change colour, dim, blink/flash, and much more based on various triggers setup by the user [6]. The Philip Hue bulbs screw easily into conventional light bulb sockets and once turned on can be connected to the Philips Hue bridge, which connects into the dwellings wireless router and allows for the lights to be controlled wirelessly by various triggers. The lights are then connected to a smartphone via the Philips Hue application.

Philips Motion and Daylight Sensor

The motion sensor acts as one of the triggers mentioned in the overview of the Philips smart light bulbs and can sense both motion and lighting levels. With this information, it can then be set to automatically control the smart lights to increase their efficiency by only turning on when light is needed and turning off when occupants are no longer present in the room [6]. The motion sensor is connected into the Internet via the Phillips Hue bridge which allows the motion sensor to communicate with other wireless enabled control points throughout the home.

7.2.3. Setup and Configuration of Smart Home Energy System

In the detached home, the sensor and control devices were located on all three floors, with the Smappee energy meter and wireless hubs in the basement, the Philips smart lights and motion sensor, Samsung temperature sensors and window contact sensors, Ecobee smart thermostat, and smart plugs on the main floor, and two Wemo smart plugs on the top floor. The approximate locations of all the sensors and controls installed in the detached home are shown in Figures 7.1a, 7.1b, and 7.1c and in the condo unit are shown in Figure 7.1d.

For the detached home, three smart bulbs were placed in the living room area, which covered all the lighting in this room, and two bulbs were installed in the kitchen. For the condo unit, the five smart bulbs were installed in the kitchen/living room area, covering all the lighting in this region of the condo. These locations in both the condo unit and detached home were chosen as they are areas that the occupants commonly leave lights on when they leave the room or their home. The motion sensor was implemented in the kitchen area to add some increased automation and resiliency to lights being left on in this area of the house, automatically turning the lights off when no motion is detected. The automation and connectivity between the lights and motion sensor was facilitated by the Philips Hue smart phone application. Variations of the logic flow outlined in Chapter 6 were used to control the lighting system. The following are some of the schedules and

programs used to improve the resiliency of the lighting system using the Philips smart bulbs and motion sensor.

Detached Home - Program 1: Living room lights turn off at 9am in the morning if left on by occupants when they go to work, and turn off at 11pm if left on by occupants after going to bed.

Detached Home - Program 2: Kitchen lights turn on and off according to motion sensor and daylight availability.

Condition 1: If motion is detected.

Condition 2: If daylight cannot provide enough lighting to meet minimum threshold.

Action 1: Turn lights on in kitchen. Light remain on until motion is not detected for 10 minutes.

Condo Unit- Program 3: Kitchen and living room lights turn on and off according to motion sensor and daylight availability.

Condition 1: If motion is detected.

Condition 2: If daylight cannot provide enough lighting to meet minimum threshold.

Action 1: Turn lights on in kitchen and living room area. Lights remain on until motion is not detected for 10 minutes.

HVAC System

Both the Ecobee thermostat as well as contact/temperature sensors were the select devices used in improving the efficiency of heating and cooling the two different dwellings. In the detached home, one of the contact/temperature sensors was used as a contact sensor on one of the kitchen windows and the other as a temperature sensor on the exterior of the home. The combined feedback from these sensors into the Ecobee thermostat allowed for better control of the HVAC system while preventing wasted energy. The automation and connectivity between the thermostat and contact/temperature sensors was facilitated by the Samsung Smart Things application. The following are the various scenarios and automations used to improve the HVAC energy performance in the detached home.

Program 1: Cooling of indoor space using outdoor air without HRV available.

Condition 1: If the Ecobee thermostat senses an indoor temperature above the cooling set-point.

Condition 2: If exterior temperature sensor senses an outdoor air temperature of $<1^{\circ}\text{C}$ below the indoor temperature set-point.

Action 1: Turn Ecobee Thermostat mode to “Off”.

Action 2: Send notification to occupant “Use outdoor air to naturally cool your home instead of mechanical cooling, mechanical system has been turned off”.

Program 2: Turning thermostat on when outdoor air cannot provide cooling.

Condition 1: If the Ecobee thermostat senses an indoor temperature above the cooling set-point.

Condition 2: If exterior temperature sensor senses an outdoor air temperature of = or > than the cooling set-point.

Action 1: Turn Ecobee thermostat mode to “On”.

Action 2: Send notification to occupant “Outdoor air is no longer available for natural cooling, mechanical system has been turned on”.

Program 3: Window open, no mechanical heating or cooling allowed.

Condition 1: If contact sensor senses that window is open

Action 1: Turn Ecobee thermostat mode to “Off”.

Action 2: Send notification to occupant “Mechanical heating and cooling has been turned off, close window to turn back on”.

Program 4: Temperature setback and setup

Condition 1: If occupants are sensed as not being home (using motion sensors and geolocation of their smartphones).

Action 1: Cooling set-point pushed up to at least 27°C or 3°C above set-point.

Action 2: Heating set-point pushed down to at least 17°C or 3°C below set-point.

Program 5: Efficient temperature set-point. Temperature set to 24°C for cooling and 19°C for heating

The Ecobee thermostat has network capabilities and connectivity to local weather stations that allow for viewing indoor and outdoor air temperature information on a mobile/desktop interface. 5 minute intervals of indoor and outdoor temperature data were able to be analyzed for the spring months of March, April, and May to quantify the

amount of overheating occurring in the condo unit and the availability of outdoor air for natural cooling. Overheating was quantified as anytime the temperatures inside the condo unit hit 25°C or higher (upper limit of the ASHRAE 55 standard).

Appliance and Electronics

The four smart plugs and smart energy meter worked together and individually to help the occupants reduce their appliance electricity consumption. The smart plugs were installed in the home office, living room, master bedroom, and kitchen areas of both the detached home and condo unit. In the detached home, the living room entertainment area was on the main floor of the home, where a speaker system, flat screen TV, and Nintendo Wii were located. The home office is located on the top floor of the home, where a laptop computer, printer, and speaker system are used. Table 6.4 provides the breakdown of what devices were connected into each of the smart plugs in the two dwellings. The smart home energy meter was connected into the home electrical system through the electrical panel which was located on the basement floor of the detached home and main floor of condo unit.

Table 7.4: Electronics connected to smart plugs

Specifications	Detached Home	Condo Unit
Smart Plug 1 – Living Room	Flat screen TV, Speaker system, Wii	Flat screen TV, Speaker system, Wii
Smart Plug 2 – Home Office	Printer, laptop computer, speaker system	Laptop computer, speaker system
Smart Plug 3 – Master Bedroom	Flat Screen TV	Flat Screen TV
Smart Plug 4 - Kitchen	Coffee Maker	Coffee Maker

The following are the various scenarios and automations used to decrease the electricity consumption of electronics and appliances.

Detached Home and Condo Unit - Program 1: Plug 1 Phantom load reduction.

Condition 1: If between the hours of 9am and 4pm and 10pm and 7am during week days, or

Condition 2: If all electronics on plug 1 are sensed as off by Smappee energy meter.

Action 1: Turn power to electronics “Off”.

Detached Home - Program 2: Plug 2 phantom load reduction .

Condition 1: If between the hours of 10pm and 7am during week days, or

Condition 2: If all electronics on plug 2 are sensed as off by Smappee energy meter.

Action 1: Turn power to electronics “Off”.

Condo Unit - Program 2: Plug 2 phantom load reduction .

Condition 1: If between the hours of 9am and 4pm, and 10pm and 7am during week days, or

Condition 2: If all electronics on plug 2 are sensed as off by Smappee energy meter.

Action 1: Turn power to electronics “Off”.

Detached Home and Condo Unit - Program 3: Plug 3 phantom load reduction

Condition 1: If between the hours of 9am and 4pm and 10pm and 7am during week days, or

Condition 2: If TV is sensed as off by Smappee energy meter.

Action 1: Turn power to TV “Off”.

Detached Home and Condo Unit - Program 4: Plug 4 phantom load reduction.

Condition 1: If between the hours of 9am and 4pm and 10pm and 7am during week days, or

Condition 2: If coffee maker is sensed as off by Smappee energy meter.

Action 1: Turn power to coffee maker “Off”.

Detached Home and Condo Unit - Program 5: Top energy consumers in home.

Energy consumption of all electronics and appliances in each dwelling is recorded and presented to occupants through the user interface on a real-time basis. This allows for occupants to see what the top energy consumers are in their home, and take action to reduce their energy consumption if they feel it is necessary.

What follows is the results from the implementation of this smart home energy system.

7.3. Results and Analysis

7.3.1. Electronics and Appliances –Phantom Load Reductions

The biggest impact on the home energy system from installing smart plugs was in the area of phantom load reductions. Using the smart plugs, the phantom load of the electronics connected to each of the smart plugs could be viewed through the smartphone interface. Based on the type of occupants living in each of the dwellings and their schedule, the smart plugs were programmed to shutoff power to connected electronics during certain times of the day.

Each of the four smart plugs had a different set of electronic devices plugged into them, which resulted in a corresponding phantom load when not in use. Depending on the type of electronics as well as the occupants schedule, the smart plugs were than programmed to turn off the phantom loads during certain times of the day resulting in the “Hours Off”

row in Tables 7.5 and 7.6. Multiplying the phantom load at each smart plug as well as the number of hours that the smart plugs turns these phantom loads off each day, results in the corresponding daily phantom load energy savings. These are extrapolated over an entire year and then added together to get the total phantom load energy savings over the course of a year. The resulting energy savings can be seen in Table 7.5 and 7.6 with a total of 122.5 kWh/yr. in estimated annual savings found for the detached home, and 118.5 kWh/yr. of energy savings found for the condo unit. This total amount of phantom load energy saved by the smart plugs was then compared to the total amount of phantom load energy consumed by all of the electronics throughout each of the dwellings (shown in column six of Table 7.5 and 7.6). This was done by plugging a smart plug into all of the outlets with electronic devices plugged into them and measuring their energy consumption when turned off.

Table 7.5: Phantom load reductions from smart plugs – detached home

	Detached Home				
	Smart Plug 1: Living Room	Smart Plug 2: Home Office	Smart Plug 3: Bedroom	Smart Plug 4: Kitchen	Phantom load of all the electronics in the dwelling
Phantom loads	12 Wh	10 Wh	2 Wh	1.5 Wh	34.5 Wh
Hours off	16 hrs.	9 hrs.	16 hrs	16 hrs	-
Timing	10pm – 7am, 9am – 4pm	10pm – 7am	10pm – 7am, 9am – 4pm	10pm – 7am, 9am – 4pm	-
Energy	192 Wh/day 70 kWh/yr.	90 Wh/day 33 kWh/yr.	32 Wh/day 11 kWh/yr	24 Wh/day 8.5 kWh/yr	750 Wh/day 274 kWh/yr.
	Smart plugs save 122.5 kWh/yr in phantom loads. This is 45%* of total phantom load energy consumption.				

**This is calculated by dividing the total plug load energy saved by the smart plugs by the total phantom load energy consumption of the dwelling (column six).*

Table 7.6: Phantom load reductions from smart plugs – condo unit

	Condo Unit				
	Smart Plug 1: Living Room	Smart Plug 2: Home Office	Smart Plug 3: Bedroom	Smart Plug 4: Kitchen	Total phantom loads in the dwelling that can be reduced
Phantom loads	10 Wh	7 Wh	2 Wh	1.5 Wh	26.5 Wh
Hours off	16 hrs.	16 hrs.	16 hrs	16 hrs	-
Timing	10pm – 7am, 9am – 4pm	10pm – 7am, 9am – 4pm	10pm – 7am, 9am – 4pm	10pm – 7am, 9am – 4pm	-
Energy	160 Wh/day 58 kWh/yr.	112 Wh/day 41 kWh/yr.	32 Wh/day 11 kWh/yr	24 Wh/day 8.5 kWh/yr	510 Wh/day 185 kWh/yr.
	Smart plugs save 118.5 kWh/yr in phantom loads. This is 64%* of total phantom load energy consumption.				

**This is calculated by dividing the total plug load energy saved by the smart plugs by the total phantom load energy consumption of the dwelling (column six).*

Compared to the total phantom loads calculated using the smart plugs connected to various electronics throughout each of the dwellings, the amount of energy being saved by the smart plugs is 45% of the detached homes total phantom load and 64% of the condo units total phantom load. For a full breakdown of the sources of phantom loads in each of the dwellings, see Appendix B.

Using the Smappee energy metering system, the total energy consumption and “Always on” portion of energy consumption were found for each of the dwellings. Table 7.7 shows that approximately 25% of total energy consumption is from sources that are always on. The total phantom load makes up about 10% of the detached home energy consumption, while the portion of phantom loads that is reducible by using smart plugs is approximately 8%. In the condo unit, these values are closer to 12% and 9% respectively.

Table 7.7: Energy consumption breakdown of dwellings

Energy Consumption Type	Description	Detached Home		Condo Unit	
		Per day	Per year	Per day	Per year
Total	Total electricity consumption from all appliances and electronics	8.9 kWh	3251 kWh	5.6 kWh	2031 kWh
Always on	Portion of electricity consumption that is always being consumed by appliances and electronics	2.2 kWh	815 kWh (25%)*	1.2 kWh	453 kWh (22%)*
Total phantom load	Portion of electricity consumption that is from electronics and appliances while turned off or on standby	0.87 kWh	317 kWh (10%)*	0.67 kWh	245kWh (12%)*
Phantom load that can be eliminated	Portion of phantom load that can be eliminated using smart plugs	0.75 kWh	274 kWh (8%)*	0.51 kWh	185 kWh (9%)*

*(%) represents the percent of total energy consumption that the portion in question represents

The calculated (using smart plug information and individual appliance energy consumption data measured through Smappee) annual energy consumption of the sources estimated to make up the “Always on” portion of energy consumption compared quite closely to that of the “Always on” energy consumption measured by Smappee. This provides confidence that the phantom loads measured using the smart plugs are accurate and can provide a good indication of the type of energy savings possible by using smart plugs. This energy breakdown can be seen in Table 7.8.

Table 7.8: Always on energy consumption breakdown

Sources	Detached Energy Consumption	Condo Unit Energy Consumption
Phantom load	317 kWh/yr.	250 kWh/yr.
Refrigerator 1	(50% of total) 200 kWh/yr.	(50% of total) 182 kWh/yr.
Refrigerator 2	(50% of total) 200 kWh/yr.	-
Wireless hubs and router	110 kWh/yr.	61 kWh/yr.
Calculated “Always on”	827 kWh/yr.	493 kWh/yr.
Measured “Always on”	815 kWh/yr.	453 kWh/yr.

7.3.2. Electronics and Appliances – Operating Load Reductions

Dryer

Using the Smappee energy meter, the appliances consuming the most energy in each of the dwellings was determined. The dryer ranked as one of the top energy consumers at about 750 Wh/cycle in the detached home. Data collected by the Smappee smart energy device showed that the dryer was being used an average of 3x times (cycles) per week in the detached home, meaning the occupants were on track to consume close to 120 kWh/yr. from dryer use. This information motivated the occupants to try and reduce their dryer usage to save energy. To do this the occupants took two actions: 1) drying their clothes as often as they could, and 2) consolidating their loads of laundry. This reduced their dryer usage to an average of 0.5x/week, bringing them on track to consume 20 kWh instead of 120 kWh, a reduction of about 100 kWh per year. The impact of consolidating their loads of laundry also had an impact on washing machine energy usage, which is touched on in the next paragraph.

Washing Machine

As mentioned previously, information on dryer usage motivated the occupants to consolidate their loads of laundry from 3x per week to approximately 1.5x per week. As a result, the annual energy consumption projected by the smart home energy system for washing machine use was cut in half, from 60 kWh to 30 kWh.

Refrigerator Lights

An interesting find by the smart home energy system was that the fridge lights were using so much energy that the smart energy meter could identify their energy usage whenever the fridge or freezer door opened and the lights turned on. A simple change from the two fridge light bulbs consuming 70 Watts and the freezer light consuming 40 watts to 3 LED bulbs that consumed 3 Watts each, resulted in 3 kWh/year of energy savings.

7.3.3. Lighting

Using the Philips Hue smart lighting in particular areas of the home, the smart energy system was able to mitigate certain faults associated with lights being left on when the occupants had left the room or home. The amount saved from this system is estimated based on the study conducted in Chapter 4 that quantified occupant faults.

7.3.4. HVAC

Using the Ecobee thermostat installed in the condo unit, the hourly temperatures both inside and outside were captured for the three primary months that make up the Spring season, March, April, and May. It was found that during these three months, overheating

occurred for a total of 462 hours or about 20% of the time. Fortunately, during times of overheating, the outside temperature was below the inside temperature of the condo unit for almost 100% of the time. Figure 7.2 shows the amount of hours of overheating that occur during each month of spring and the amount of hours the outdoor air is below the inside temperature when overheating occurs. Table 7.9 provides a breakdown of the percent of time that outdoor air would be available to help cool the inside environment instead of mechanical cooling when overheating occurs during the period analyzed (March – May). Based on these findings, a study was conducted to investigate what the potential energy and cost savings from using natural cooling might be in a condo unit. This study is outlined in Chapter 8.

Figure 7.2: Hours of condo unit overheating and cooling availability of outdoor air

Table 7.9: Summary of hours of overheating and hours that outdoor air is available for natural cooling

	March	April	May	Total
Indoor temp. > 25°C (Overheating)	31 hrs.	65 hrs.	366 hrs.	462 hrs.
Outside temp. is >10°C below inside temp. during overheating	31 hrs. (100%)	47 hrs. (73%)	84 hrs. (23%)	163 hrs. (35%)
Outside temp. is >5°C below inside temp. during overheating	-	65 hrs. (100%)	228 hrs. (62%)	324 hrs. (70%)
Outside temp. is >1°C below inside temp. during overheating	-	-	346 hrs. (94%)	442 hrs. (96%)

7.3.5. Occupant Qualitative Feedback and Insights

The fact that energy savings along with other quantitative data insights were achieved through the implementation of this system is only a portion of the benefits obtained through conducting this prototype test. The other benefits achieved were the qualitative insights and findings gathered from creating a functioning smart home energy system. The first insight was that these smart devices are not very smart until properly programmed to carry out the desired tasks and connected to the rest of the system. For example, the window sensors, once installed, will tell the occupants when a window opens and closes, however, if no more is done to integrate them into the system, they are no more intelligent than a contact sensor from 2005, which was before the idea of smart devices and smart homes really took off and everything was labeled as “smart”. These devices only start to become smart and add intelligence to a home, when two things happen; They inform the home energy system to operate with a greater intelligence or more energy efficiency than it did before and when they provide the occupant insights rather than just information. The difference being that in the case of an insight, the device or system takes information collected by the sensors or control points, analyzes it, and adds additional information to tailor it to the needs of the occupant, which in this case are to

reduce home energy consumption. Another finding that speaks to the need for these smart devices to be programmed and connected properly, is the potential inconvenience and discomfort they can cause the occupant. During this prototype test, there were several times that elements of the smart system had to be reprogrammed to change triggers or reduce the frequency of notifications sent to occupants. Increased notifications coming from the smart system were usually a result of the system sending information without doing enough analysis to provide only the key pieces of information necessary to provide value to the occupant. One example of this pertains to the cooling system where outdoor air was being encouraged for use in naturally cooling the home. The outdoor temperature sensors were originally sending notifications that outdoor air was available for natural cooling every time the outdoor temperature dropped below the cooling set-point.

However, this caused unnecessary notifications to be sent to occupants during times when no cooling inside was necessary. To fix this and provide less notifications to occupants that were of more value, the system was reprogrammed to only send notifications when both outdoor air was below the indoor cooling set-point, and cooling was required inside the home. The information was also packaged with a call to action which was that occupants should go and open their windows. Armed with the necessary information, occupants can easily install and configure this smart home energy system themselves at next to no cost. Operationally, the only costs that are foreseeable are that of battery replacements for some of the sensors.

The second insight from doing this prototype test was occupant fatigue with the smart energy system. The occupants began to lose interest in the smart system after the initial ‘wow’ factor of having a smart home energy system had subsided. What helped keep them engaged was being able to see what the top energy consumers were in their home as

well as receiving calls to action from the smart system. Without the calls to action long with the information that was provided to them, it is not likely that the occupants would have ever taken the time to do things like open windows to allow for natural cooling to happen. This feedback is important for future research into smart home design development, being that action requests are better than just providing information to occupants and expecting them to take an action or know what action to take. It is also possible that with the use of gamification, occupants would have been more motivated to take further actions, however with only one smart home energy system to test with, gamification and competition among users could not be implemented.

The most fundamental achievement of this system, and possibly the most profound was that the smart home energy system was able to make occupants aware that actions they take in their home have a related consequence on their energy consumption. This was made possible by the real-time and daily notifications that the smart home system provided to occupants on their energy consumption habits and uses. One of the primary goals of this system was changing occupant behaviour to be more energy efficient, and even though this is hard to quantify, the awareness that actions equal energy consequences that was realized by the occupants in this test, is a good indication that a behaviour change is occurring or at the very least is the change in mindset right before it occurs.

7.4. Conclusion

Results show the system provides a degree of benefit to the occupant that makes the implementation of this system feasible over the long term. The test was not able to analyze the full extent of the smart home energy system, however the parts of the system

that were analyzed show that energy savings are achievable. These savings consisted of about 120 kWh from phantom loads and 130 kWh from major appliances. The savings for other areas of the implementation of the smart home system have been simulated (Chapters 3, 4, and 8) as well as backed up by previous literature. Table 7.10 summarizes the energy saving results quantified for the systems analyzed as part of this prototype test. The energy savings presented here were achieved with changes that were made within a short time frame of a couple months, and although the results were limited in terms of quantifying energy savings, it still provides increased confidence that this system can achieve the energy savings that have been simulated and estimated in Chapter 6. Depending on when these energy savings occur during the day, savings on energy costs for the detached house would be between \$16 and \$33 per year and for the condo unit between \$7 and \$15 per year. Even though the monetary savings may not seem significant, it is important to consider that this is only one part of the home energy system. It is also important to consider the positive impact these energy savings have on environment could be much more valuable than the monetary savings.

Table 7.10: Summary of annual energy savings achieved by the smart home energy system through testing

	Detached House	Condo Unit
Phantom Load Reductions	122.5 kWh	118.5 kWh
Improved Operating Efficiency of Largest Energy Consuming Appliances	Dryer: 100 kWh Washing Machine: 30 kWh Fridge Lights: 3 kWh	
Estimated Total Energy Consumption of Dwelling	3250 kWh/yr	2030 kWh/yr
Total	255.5 kWh (7.5%)*	118.5 kWh (5.8%)*

*This value represents the energy savings as a percent of the dwellings total electricity consumption. It was calculated by dividing the total electricity savings by the total electricity consumption of the dwelling estimated using the Smappee smart energy meter.

The qualitative results and insights obtained from the implementation of this smart home energy system provide learnings as to the importance of properly connecting and

programming elements of the system to provide the best value to occupants with the least amount of notifications. By thinking critically about each piece of the system and ensuring that it is providing information to the occupants that is either an insight or an action, or that it is contributing information to other elements of the smart home energy system to help them provide either the system or occupants with insights and actions, the whole system will operate with greater intelligence. Ultimately this means meeting its intended objectives and that of the occupants, which are to increase the energy efficiency of their home. Possible the most profound result of this system was that it caused the occupants to realize that every action they take in their home has an effect on their home energy consumption, whether this be negative or positive. This is a critical step in creating a change in occupant behaviour to more efficient energy consumption, one of the main goals of this smart home energy system. Figure 7.3 provides a summary of the key qualitative insights from the smart home energy system prototype test.

Figure 7.3: Summary of qualitative results and insights obtained from the smart home energy system through testing

In order to be more confident about the results obtained in this study, a longer testing period would be used that spans at least one year. This would help overcome the issue with quantifying the impact of the smart home energy system on heating and cooling energy consumption. It would also provide a longer period of time for assessing how occupant behaviour and motivations change as the novelty of the smart home system wears off. For gaining further occupant insights as to the usability and benefits of the smart home energy system, future studies of this system should seek to use occupants who do not have potential bias in the outcomes of the system.

The next chapter, Chapter 8, serves to further back up the savings estimated by this smart home energy system test, by providing a detailed account of the simulation study conducted on the potential for using outdoor air instead of mechanical means to achieve cooling energy savings.

7.5. References

- [1] Swiss Federal Office of Energy. “ewz-Amphiro Study: The effectiveness of Real-Time Feedback.” pp.2. 2014.
- [2] Smappee. “Smappee Energy.” Internet: https://www.smappee.com/ca_en/home ,2018.
- [3] Belkin. “Wemo Switch Smart Plug.” Internet: <http://www.belkin.com/us/p/P-F7C063/> , 2018.
- [4] Ecobee. “Ecobee4.” <https://www.ecobee.com/ecobee4/> , 2018.
- [5] Samsung. “Sensors.” Internet: <https://www.samsung.com/us/smart-home/smartthings/sensors/f-mlt-us-2-f-mlt-us-2/> , 2018.
- [6] Philips Hue. “Hue Products.” <http://www2.meethue.com/en-ca/> , 2018.

8. Feasibility of Natural Cooling Provided by an ERV Bypass

8.1. Introduction

With a large amount of cooling required by condo and apartment units during times that outdoor temperatures are multiple degrees below the indoor temperature set-point, there lies the opportunity to utilize colder outdoor air to provide space cooling that offsets mechanical means of cooling. To utilize this free cooling, the outdoor air must have a temperature that is below the indoor set-point as well as be brought into the space at a rate that ensures cooling demands are met. Natural cooling must meet enough of the cooling demand that the associated energy and cost savings make the implementation of a technology to provide outdoor air into the space, feasible. The technology that will be assessed for its feasibility in the capacity of providing natural cooling to the space, is an ERV unit with outdoor air bypass. This analysis will determine the feasibility of using an ERV bypass to supply outdoor air into a condo unit and provide natural cooling as a means to offset mechanical cooling loads.

An ERV is a mechanical device used for exchanging the energy contained in air being exhausted from a space to outside air coming into a space. During the warmer months, the system pre-cools and dehumidifies while humidifying and pre-heating in the cooler seasons. Figure 8.1 represents the basic flow pattern through the core of a ERV during both bypass and non-bypass mode.

Figure 8.1: Air flow through an ERV with bypass on and off

8.2. Methodology

The methodology for determining the feasibility of natural cooling provided by an ERV bypass was broken down into three major areas that had to be considered.

1. The type of apartment unit that would be modelled and its specifications,
2. The type of ERVs that would be modelled and their specifications, and
3. The steps required to model both the unit and ERV in order to ensure the necessary results were produced for determining the feasibility of an ERV bypass to meet cooling load demand.

8.2.1. Building Unit Specifications

To investigate the feasibility of natural cooling supplied by an ERV bypass, a 120 m² apartment unit from a conventional residential building (built to National Energy Code for Buildings (NECB) 2015), similar to the conventional building unit in Chapter 3, was

simulated. The location of the building is set in Ottawa Ontario and the unit is South facing. The model was developed using the BPS tool EnergyPlus in conjunction with Open Studio. The unit has dimensions $W \times L \times H = 12\text{m} \times 10\text{m} \times 3\text{m}$ with a window of $W \times H = 6\text{m} \times 2\text{m}$ and sill height of 0.8m. The boundary conditions for the interior surfaces were considered adiabatic, since they are adjacent to spaces with similar thermal conditions. Only the South-facing wall was exposed to outdoor conditions based on the 2016 EPW weather file for Ottawa Macdonald Cartier International Airport used in this analysis. Design and operating parameters for the unit are provided in Table 8.1 below.

Table 8.1: Input design and operating parameters for unit modelled

Design and Operating Parameters	Conventional MURB
Exterior wall U-value ($\text{W/m}^2\text{K}$)	0.247
Windows U-value ($\text{W/m}^2\text{K}$)	2.2
Windows SHGC	0.45
Windows visible transmittance	0.8
WWR	37%
Fresh air supply rate	2.5 L/s person + 0.3 L/s.m ² (ASHRAE Standard 62.1, 2013)
HVAC type	Ideal load system

The unit was assumed to have an occupant density of 60 m²/person (i.e. two occupants per unit) per NECB 2015. The occupant schedule was also created according to NECB which assumes lower occupant (30%) between 8 AM and 5 PM on weekdays, and a slightly higher occupancy during these hours on weekends (50%). Occupant schedules for all cases were based on NECB 2015 to focus only on occupants' interaction with the building systems, rather than the durations of their presence within the units.

8.2.2. ERV Unit Specifications

The ERV chosen for this analysis is from a company called [HOLTOP](#), the leading manufacturer of air to air heat recovery equipment in China. Holtop is one of the few

ERVs with an automatic bypass and specifications readily available [1]. Table 8.2 outlines the five ERVs that were modelled from HOLTOP along with the Omega ERV unit that does not have a fresh air bypass and is currently being installed by Zibi. The reason for including the Omega ERV in this analysis, is to determine the difference in pricing and the payback period to recuperate the additional costs needed for a bypass equipped ERV.

Table 8.2: HOLTOP and Omega ERV specifications

	Size	Power	Air Flow	Price	Details
HOLTOP ERV [1] (XHBQ-D1.5DCTPA) Link , Link 2	(H x W x L) 32" x 10"x 22" Mass: 25 kg	26 W	88 cfm (150 m ³ /h) 31.5 dB(A)	\$515 (USD) [3]	-Counter flow heat exchanger -Auto bypass -Counter flow heat exchanger
HOLTOP ERV [1] (XHBQ-D2.5DCTPA) Link	(H x W x L) 32" x 10"x 22" Mass: 29 kg	46 W	147 cfm (250 m ³ /h) 34.5 dB(A)	\$530 (USD) [3]	-Energy saving BLDC motor, 10 speeds control -Electric preheat/reheat connector
HOLTOP ERV [1] (XHBQ-D3.5DCTPA) Link	Mass: 37 kg	60 W	205 cfm (350 m ³ /h) 37.5 dB(A)	\$581 (USD) [3]	-CO2 concentration control -Multiple auto defrosting mode,
HOLTOP ERV [1] (XHBQ-D5.0DCTPA) Link	Mass: 43 kg	88 W	294 cfm (500 m ³ /h) 39 dB(A)	\$654 (USD) [3]	outdoor operation temperature down to -15°C
HOLTOP ERV [1] (XHBQ-D20DCTPA) Link	Mass: 189 kg	486 W	1117 cfm (2000 m ³ /h) 51.5 dB(A)	\$1945 (USD) [3]	
Omega ERV	(H x W x L) 34" x 9"x 20" Mass: 23 kg	70 W (2 motors)	90 cfm (152 m ³ /h)	\$500 [4] (prices range from \$500 to \$1,700 USD for ERV)	-Two backward inclined DC fans. -10V DC signal -Freeze protection

8.2.3. Feasibility Metrics

The metrics used to determine whether the ERV bypass is a feasible method for providing cooling when utilizing outdoor air, were identified as:

1. Metric 1: The amount of annual cooling load that can be met by the ERV bypass natural cooling. Measured in both the percent and kWhs of thermal and electrical energy offset.
2. Metric 2: The amount of dollars saved annually on cooling electricity that has been offset by natural cooling as well as the payback period for recouping the additional costs associated with a bypass ERV as opposed to an ERV with no bypass function.

There were numerous steps involved in quantifying these metrics. First, the hourly zone cooling rate had to be found for the unit modelled. The hourly cooling consumption was then divided by what hours it fell on during the day to determine the amount of cooling thermal energy consumed during off-peak, mid-peak, and on-peak hours. To determine the amount of this hourly cooling load that could be offset by natural cooling, the hourly indoor and outdoor temperatures for the space were outputted. Using Equation 8.1 below and the mass flow rate of air specified by the ERV, the hourly natural cooling availability in watts was found. The availability of natural cooling was further refined by considering humidity levels and ensuring that indoor humidity levels were not increased by incoming outdoor air. This was done by limiting the absolute humidity of incoming air to that of the absolute humidity level of indoor air at a temperature of 24°C and 60% relative humidity (RH). The RH level chosen is within the comfort range set out by ASHRAE, which recommends that indoor relative humidity levels stay below 65% [8]. Absolute humidity

levels at this indoor RH and temperature are approximately 0.0132 kg/m^3 . Using the hourly cooling demand and hourly natural cooling available, the amount of cooling energy that could be offset during off-peak, mid-peak and on-peak hours of the year was determined.

The electrical energy consumed by the fan was subtracted from the electrical energy that was saved by using ERV natural cooling instead of mechanical cooling with a heat pump. This was done to determine the net cooling electrical energy savings. Fan energy consumption was determined using the flow rate that would be needed by the ERV to meet the cooling demands of the space for any hour of the year. For every hour of the year, the fan energy consumption was then compared to the heat pump energy consumption, to ensure the ERV providing natural cooling wasn't consuming more energy than the heat pump would require to provide the equivalent amount of cooling. Appendix C shows the step by step calculations used to determine the fan energy consumption. Density of air was constant at 1.225 kg/m^3 based on standard temperature (15°C) and pressure (101.3 kPa). This value is reasonable for the conditions under which natural cooling was predominantly used, which was when outdoor temperatures were between 10°C and 20°C .

$$Q = MC\Delta T = \rho V C \Delta T \quad (\text{Equation 8.1})$$

- ρ : Density of air - 1.225 kg/m^3
- C: Specific Heat Capacity of air – 1.003 KJ/kg K
- Q: Heating or Cooling Energy - KJ/h
- V: Volumetric Flow Rate - m^3/h

- M: Mass Flow Rate - kg/h
- ΔT : The temperature difference between indoor and outdoor temperature (K)

Metric 2 was found by multiplying the price per kWh during off-peak, mid-peak, and on-peak times by the amount of cooling energy saved during that time. Payback period was then found by dividing the price difference between the HOLTOP ERV and Omega ERV by the annual cooling energy cost savings. Figure 8.2 below shows the time of use pricing for Ontario that was used. Cost analysis was also done using electricity pricing for Quebec which was taken as 10.3 cents/kWh for this building based on its average and peak consumption. An in-depth example calculation of how metrics 1 and 2 were calculated can be found in Appendix C.

Figure 8.2: Time of use pricing for Ontario

8.3. Results and Discussion

8.3.1. Energy Savings

After following the steps outlined in the methodology section, energy and financial results for all five ERV units were determined. As the air flow rate increases, the amount of energy that can be offset by the ERV also increases. Table 8.3 summarizes the thermal and electrical energy savings in kWh that can be obtained by each ERV unit.

Table 8.3: Annual thermal and electrical energy savings from natural cooling

ERV Type	Thermal Energy Savings	Heat Pump Electrical Energy Savings (COP of 3)	% of Cooling Thermal and Electrical Energy Saved
Holtop ERV 1.5	900 kWh (Net: 850 kWh)	300 kWh (Net: 285 kWh)	41%
Holtop ERV 2.5	985 kWh (Net: 950 kWh)	330 kWh (Net: 315 kWh)	45%
Holtop ERV 3.5	1025 kWh (Net: 1000 kWh)	340 kWh (Net: 330 kWh)	47%
Holtop ERV 5.0	1065 kWh (Net: 1035 kWh)	355 kWh (Net: 345 kWh)	50%
Holtop ERV 20	1145 kWh (Net: 1120)	380 kWh (Net: 375 kWh)	52%

*Energy savings were calculated based on modelling done with 2016 weather data for Ottawa

Results show that even when air flow rates reach extremely high values, the maximum amount of energy savings feasible is just over 50%. This is because in conjunction with a high flow rate, there must also be a temperature gradient between the indoor and outdoor environment as well as humidity levels within an acceptable range. There are times during the summer months that outdoor temperatures will be at or above indoor temperatures, making the use of outdoor air for natural cooling not possible during that point in time. The process of ensuring incoming outdoor air did not increase indoor humidity levels, resulted in a drop of 16% in the amount of energy savings possible using natural cooling. It is also important to note that HOLTOP models above the HOLTOP ERV 3.5, increase in size and weight to a point where they are not feasible to install in individual apartment units.

In terms of air flow rate, the ERV 1.5 unit from HOLTOP is the closest to the Omega unit being installed by Zibi in their Block 13 building. At an air flow rate of 88 cfm (or 15 m³/h), the HOLTOP ERV 1.5 unit can offset almost 40% of the summer cooling energy requirements and 80% of the winter cooling energy requirements. Figure 8.3 summarizes these results and shows a comparison between the cooling energy requirements for the apartment unit and how much of this can be covered by the ERV bypass supplying natural cooling.

Figure 8.3: Annual thermal energy consumption requirements for cooling vs amount of thermal energy that can be offset using natural cooling through bypass mode on a HOLTOP ERV 1.5 unit

8.3.2. Cost Savings

For each of the five ERV units, the cost savings were calculated based on when the energy savings occurred during the day and what the price of electricity would be based on time of use pricing outlined in Figure 8.3. With ERV models 1.5, 2.5, and 3.5, it is possible to obtain reasonable cost savings and a short payback period by using an ERV

bypass model instead of just a regular ERV (see Table 8.4 for cost savings and simple payback period). A very high air flow rate model like that of the ERV 20, produces slightly more annual dollar savings but is not feasible from a cost perspective due to its large payback period. It's size and weight specifications also do not make it applicable for a condo or apartment unit application. It was analyzed to show how extreme increases in air flow rate do not provide significant increases in energy or cost savings.

Table 8.4: Annual cost savings and payback period

ERV Type	Ontario		Quebec	
	Cost Savings	Simple Payback Period	Cost Savings	Simple Payback Period
Holtop ERV 1.5	\$23	0.7 years	\$30	0.5 years
Holtop ERV 2.5	\$25	1.2 years	\$33	0.9 years
Holtop ERV 3.5	\$27	3.0 years	\$34	2.4 years
Holtop ERV 5.0	\$28	5.6 years	\$36	4.3 years
Holtop ERV 20	\$30	48 years	\$38	38 years

*Savings take into consideration a heat pump with a COP of 3

8.4. Conclusion

This analysis shows that implementing an ERV with bypass to utilize outdoor air for natural cooling is a feasible method to offset mechanical cooling energy requirements, both from an energy savings perspective and a cost perspective. The implementation of an ERV with bypass is no different than a regular ERV, requiring no alterations to HVAC design all while utilizing the same intake and exhaust openings in the building facade.

Depending on Windmill Developments payback period requirements for investments, any one of the ERV units 1.5, 2.5, and 3.5 will provide a payback within 3 years and some

degree of energy savings regardless of which province it is located. The HOTOP ERV 1.5 is very similar to the Omega unit being installed in terms of size, weight, and air flow rate specifications and may pose as the best option for implementation. With savings of 40% on cooling energy consumption and an 8-month payback on the cost difference between a regular ERV without bypass, the ERV with bypass looks to not only be an effective solution to reducing increasing mechanical cooling loads but a very cost effective solution as well.

8.5. References

- [1] Holtop. “Energy Recovery Ventilator.” Internet:
<http://www.holtop.com/Products/Energy/2017-ECO-SMART-PLUS-ERV.html> , 2017.
- [2] Windmill Developments. “Quote 2014-620-SM02 – Suite Heat Pump.” pg 33. 2018.
- [3] Email Exchange: Rubby@holtop.com to Andrew.Hicks@carleton.ca
- [4] Dan Chiras. Energy-Recovery Ventilators: Ventilate Your Home With Minimal Energy Loss. 2010. Source: <https://www.motherearthnews.com/green-homes/energy-recovery-ventilator-zmaz09djzraw>
- [5] Zehnder America. “Thermal Reviews.” Internet:
<http://thermalreviews.com/Reviews/ProductReviews.aspx?ID=161> ,2014.
- [6] The Engineering Toolbox. “Fan Affinity Laws.” Internet:
https://www.engineeringtoolbox.com/fan-affinity-laws-d_196.html ,2018.
- [7] Design Spark. “4 reasons to use a fan speed controller in your application.” Internet:
<https://www.rs-online.com/designspark/4-reasons-to-use-a-fan-speed-controller-in-your-application> ,Aug, 2015.
- [8] Center for Disease Control and Prevention. “Indoor Environmental Quality.” Internet:
<https://www.cdc.gov/niosh/topics/indoorenv/temperature.html> ,September, 2015.

9. Conclusion

With Climate Change already wreaking havoc across the world, our society must identify ways of reducing our greenhouse gas emissions as quickly as possible to limit its escalation. A 2009 report by the United Nations states that the building stock represents the most important opportunity to substantially reduce greenhouse gas emissions, by virtue of the scale of the reductions that are possible and the economic returns from doing so [1]. In Canada, buildings account for 35% of energy consumption with the residential sector accounting for approximately half of this. There are many solutions to reducing building energy consumption, however one that is often overlooked is occupant engagement. In this thesis, an occupant in-the-loop smart home energy system is designed and implemented to explore how smart home systems can better address areas of building energy consumption that are more susceptible to occupant behaviour as well as successfully engage occupants to take a more active role in reducing their home energy consumption.

To design a smart home energy system that could successfully meet these objectives, multiple steps of research and analysis were taken. Starting in Chapter 3, a simulation study was conducted on the impact of occupant behaviour on the energy consumption of a high-performance MURB compared to a conventional MURB to understand where occupants had the most impact on energy consumption, and how their impact on the building energy consumption breakdown changes as building performance increases. In both high-performance and conventional buildings, differences in energy consumption between active and passive occupants increased by close to 60%. The key finding from

this study was the large difference in energy consumption breakdown between the two different building types, especially as behaviour type changes from active to passive. In Chapter 4, another simulation study was conducted on the impact of occupant behaviour on residential building energy consumption. Two different occupant types (active and passive) were modelled to determine the energy systems most susceptible to large variations in energy consumption due to varying occupant behaviours. This study also focused on identifying what home energy systems are most susceptible to large amounts of wasted energy from occupant faults (leaving windows open, leaving lights on, etc.). Findings from this study show that the occupant faults associated with heating and cooling cause the largest amounts of wasted energy, with an average of 600 -700 kWh/yr. of additional energy consumption per fault. Phantom plug loads, hot water heating, dryer usage, and heating and cooling were the greatest impacted by occupant behaviour. Finding from the studies in Chapters 3 and 4 helped to provide a better understanding of which energy systems should be a priority within the smart home energy system design and where to implement sensors and controls as a first priority. Chapter 5 contained the details of the next step for informing the design of the smart home energy system, which was the survey study on the behaviour of occupants when interacting with residential building energy systems. There were several very insightful findings that came out of this survey which informed both the type of information that should be sent to occupants, as well as how that information should be formatted and its frequency of delivery. These three pieces of information are arguably the most important for being able to successfully engage occupant action for reducing energy consumption. Chapter 6 contained both the back-end and front-end design development of the smart home energy system, which was based on the insights from the previous three chapters.

The result was a sensor and metering configuration containing 12 sensors and control points that provided the information necessary to carry out the logic flow design of the front end system, and ultimately provide engaging insights to occupants and automations for the system.

Chapter 7 detailed the implementation of this system in both a detached home and condo unit, identifying both benefits of this system and areas requiring either further research or improvement. Results showed energy savings of 250 kWh/year from a reduction in phantom loads and improved operation of certain major appliances. Potential savings from other functions of the smart home energy system were provided through simulation in Chapters 3, 4 and 8 and calculations based on research studies of real world implementations of certain elements of this smart home energy system. These energy savings were coupled with insights and learnings that are critical to the further development of smart home systems and smart home energy systems.

Chapter 8 described the ability of the natural cooling function of the smart home energy system to save energy and costs on space cooling. This was done to not only explore alternative options to reducing mechanical cooling requirements, but also as a way to substantiate the capabilities of the smart home energy system.

The work that has been completed here on the creation of an occupant in-the-loop smart home energy system involved research, modelling, design, and implementation, covering all possible aspects of a development process. As a result of the extensive work that went into the creation of this system, the findings made from this thesis provide significant contributions to the development of occupant engagement and smart home energy systems. Thanks to the combination of the different research studies conducted which

included both occupant participation and simulation, the information used for the development process was unique in the sense that no one had previously used this information to inform past designs. That is why the contributions presented here are significant and provide benefits that differ from past work. What also makes this work and contributions unique is the occupant engagement focus of this smart home energy system. This thesis aimed to develop a smart system that encompassed not only all major elements of the home energy system but also occupant behaviour, something that had not been sufficiently addressed in the past.

There are multiple interesting results and findings throughout the many chapters of this thesis, however the key contributions that are touched on here relate to the occupant in-the-loop smart home energy system that was developed based on all the research conducted in the earlier chapters of this thesis. The first key contribution made by this work is the smart home energy system design itself. Informed by both modelling work and occupant behaviour feedback, it provides a system that future researchers can be confident in using to gather further occupant behaviour and energy impact information. It opens the doors for increased focus on these areas without having to go through all the work of the initial system development.

The second contribution consists of the insights obtained through the implementation of this system design and experiencing its functionality. The energy savings found through testing provide confidence in the system's ability to deliver on the savings estimated during the design phase. However, the qualitative findings from the system implementation provide valuable information as to what motivates occupant engagement, what detracts from it, and what were the most useful and least useful system functions.

Figure 9.1 summarizes these valuable findings from occupants living in a smart home energy system environment. These help provide a starting point for where future work may want to start their research upon the implementation of this smart home energy system.

Figure 9.1: Qualitative insights from occupant interaction with the smart home energy system

Finally, the extensive work to quantify energy saving potential from the implementation of this smart home energy system, both through prototype testing, as well as simulation and calculations based on previous research case studies, is the third key contribution of this thesis work. It provides a baseline for what occupants, researchers, and industry professionals can hope to achieve through the implementation of various elements of this smart home energy system, or this system as a whole. Table 9.1 provides a summary of the energy savings achieved through the smart home energy system prototype testing, simulation, and calculations based on previous case studies. Variations between test results and those found through simulation and calculations are a result of different appliance types and occupant behaviour. The occupants in the prototype test are assumed

to be of average occupant type (these values were taken from Chapter 7). Simulated energy savings show the range of potential energy savings from average occupant behaviour type to passive occupant behaviour type (These were taken from Chapters 3 and 4). Calculated energy savings show the energy savings potential of an average occupant (These were taken from Chapter 6).

Table 9.1: Annual energy savings achieved by the smart home energy system

Home Energy System	Testing	Simulated	Calculated
Phantom loads	120 kWh	580 - 1100 kWh	490 kWh
Major appliances	130 kWh		-
HVAC (setpoint reductions)	-	440 - 860 kWh	340 kWh
HVAC (setbacks and setups)	-		250 kWh
Use of natural cooling	-		280 kWh
Hot water heating - showering	-	580 - 1360 kWh	430 kWh
Hot water heating – other consumers	-		-
Lighting	-	80 – 110 kWh	100 kWh

Future work should focus on the following three areas to further develop the research presented in this thesis. The first would be to conduct further real-world implementations of this system or variations of this system to better understand the energy savings potential and the success of occupant engagement provided through smart home energy systems. The variations in energy savings potential between simulated, calculated, and prototype tested results in Table 9.1 show the need for future work to delve deeper into quantifying the energy savings potential of smart home systems. Phantom loads and major appliances were the primary area of focus for quantifying energy savings with this implementation of the smart home energy system. The HVAC system and hot water

system showed great potential for energy savings based on simulation and calculation (from case study results) analysis and should be the focus of the next implementation of this smart home energy system for quantifying its energy saving potential.

In the prototype test presented in Chapter 7, the smart home energy system was implemented in two different dwelling types, however both as isolated implementations. The second area that future work should address is the implementation of this system in not only various different dwelling types, but also multiple implementations across the same dwelling type, such as condo units in the same building. This is to explore occupant engagement strategies associated with this smart home energy system that are only possible with simultaneous implementations. One of these strategies is gamification, which has been shown to be effective in helping create more energy efficient occupant behaviour, however could not be confirmed with this research work. Future work should look at the impact of gamification on engaging occupants to reduce their energy consumption in the setting of an occupant in-the-loop smart home energy system like the one presented in this thesis.

Finally, the third area of future work should delve deeper into better understanding what features and communication strategies work best to engage occupant action. The implementation of this smart home energy system showed that occupants became more aware of how their actions resulted in energy consumption based on the real-time feedback of their energy consumption information. However, a majority of the design for this smart home energy system was based on occupant survey results. Further iterations could provide valuable feedback as to how occupants behave as opposed to how they say

they behave (which is what the survey results from this thesis research provided) and can be used to refine the smart home energy system design to better engage occupants. Learnings from occupant interactions with the smart home energy system are extremely valuable and should be analyzed further in order to expand on the work done here.

This thesis provides a foundation from which further research on occupant behaviour interaction with smart home energy systems as well as on the energy impacts of smart home systems can be carried out.

9.1. References

[1] CaGBC, 'Building Solutions to Climate Change', September 2016. [online].

Available:

https://www.cagbc.org//cagbcdocs/2016_Building_Solutions_to_Climate_Change_Public.pdf. [Accessed: 2-Nov-2017]

10. Appendix

The references in the appendix refer back to the references of the chapter which each specific Appendix refers to. Therefore all references in Appendix A – Chapter 6 refer back to the reference section in Chapter 6.

10.1. Appendix A – Chapter 6

In order to determine what the percent savings of total condo unit electricity consumption would be for each of the smart home devices analyzed in Chapter 6, an annual total energy consumption of the condo unit had to be determined. The Ontario Energy Board (OEB) sets the standard definition of a typical residential customer's annual energy consumption to be 9000 kWh [19]. The following sections outline how the energy savings were calculated for each of the smart home energy devices presented in Chapter 6.

Programmable thermostat heating and cooling setback and setup savings

Natural Resources Canada found from their research of an energy efficient R2000 test home, that 10-13% savings on heating energy and 11% savings on cooling energy can be obtained from efficient temperature setbacks and setups [17]. This is slightly lower than the Energy Star estimates of 5.4% savings per °C of setback [17]. Below are the calculations and analysis for estimating the energy savings achievable through a programmable thermostat installed in the condo unit simulated in Chapter 4.

Base heating and cooling energy consumption for condo unit (Based on simulation studies conducted in Chapter 4):

North unit heating: 1135 kWh/year

South unit heating: 444 kWh/year

- Average heating energy consumption = 800 kWh/year (10 – 13% of this is 80 – 100 kWh/year)

North unit cooling: 1119 kWh/year

South unit cooling: 1191 kWh/year

- Average cooling energy consumption = 1155 kWh/year (11% of this is 130 kWh/year)

In total, heating and cooling energy savings (~220 kWh), result in a 2.4% savings in total electricity requirements of the condo unit (220 kWh/9000 kWh).

Smart thermostat heating and cooling setback and setup savings

Nest research studies from users with Nest thermostats have found that on average their smart thermostat results in 10% heating energy savings and 15% cooling energy savings [12].

Base energy consumption for condo unit (Based on simulation studies conducted in Chapter 4):

North unit heating: 1135 kWh/year

South unit heating: 444 kWh/year

- Average heating energy consumption = 800 kWh/year (10% of this is 80 kWh/year)

North unit cooling: 1119 kWh/year

South unit cooling: 1191 kWh/year

- Average cooling energy consumption = 1155 kWh/year (15% of this is 170 kWh/year)

In total, heating and cooling energy savings (250 kWh) result in a 2.8% savings in total electricity requirements (250 kWh/9000 kWh).

Savings from temperature set-point

Base temperature set-points for the North and South units are 21°C in the winter (with an 18°C setback temperature), and 24°C in the summer. Potential savings could result if the winter temperature set-point was set lower and the summer temperature set-point was set higher. The 2011 SHEU report (Survey of Household Energy Use report) provides backup for our choice of various set-points [20]. The following is how savings were determined for temperature set-point choice.

Heating set-point savings (based on simulation studies conducted in Chapter 4):

North unit heating (Base setpoint at 21°C and 18°C setback): 1135 kWh

South unit heating (Base setpoint at 21°C and 18°C setback): 444 kWh

Average heating energy consumption = 800 kWh

North unit heating (low setpoint 19°C and 18°C setback): 901 kWh

South unit heating (low setpoint 19°C and 18°C setback): 251 kWh

Average heating energy consumption = 576 kWh

Savings = 224 kWh or 2.5% (224/9000)

Cooling set-point savings (based on simulation studies conducted in Chapter 4):

North unit heating (base setpoint 24°C): 1119 kWh

South unit heating (base setpoint 24°C): 1191 kWh

Average heating energy consumption = 1155 kWh

North unit heating (high setpoint 25°C): 1010 kWh

South unit heating (high setpoint 25°C): 1071 kWh

Average heating energy consumption = 1040 kWh

Savings = 115 kWh or 1.3% (115/9000)

Electricity savings from smart plugs

The following is what would be assumed to be plugged into the various smart plugs, starting with the first one implemented and then expanding from there. It also shows the phantom load that would be eliminated using the smart plugs.

TV:	$6.4 \text{ watts} \times 20 \text{ hrs standby/day} \times 365 \text{ days/year} = 46 \text{ kWh/year}$
Cable Box:	$17.83 \text{ watts} \times 20 \text{ hrs standby /day} \times 365 \text{ days/year} = 130 \text{ kWh/year}$
Sound System:	$8.32 \text{ watts} \times 20 \text{ hrs standby /day} \times 365 \text{ days/year} = 60 \text{ kWh/year}$
Microwave:	$2.8 \text{ watts} \times 23.78 \text{ hrs standby /day} \times 365 \text{ days/year} = 24 \text{ kWh/year}$
Coffee maker:	$1.14 \text{ watts} \times 23.5 \text{ hrs standby /day} \times 365 \text{ days/year} = 10 \text{ kWh/year}$
Laptop charger:	$4.42 \text{ watts} \times 19 \text{ hrs standby /day} \times 365 \text{ days/year} = 30 \text{ kWh/year}$
Range:	$2.2 \text{ Watts} \times 23.2 \text{ hrs standby /day} \times 365 \text{ days/year} = 18.6 \text{ kWh/year}$
Printer (inkjet/laser):	$4.2 \text{ Watts} \times 23 \text{ hrs standby/day} \times 365 \text{ days/year} = 35 \text{ kWh/year}$
LCD Monitor:	$2 \text{ Watts} \times 19 \text{ hrs standby/day} \times 365 \text{ days/year} = 14 \text{ kWh/year}$

The phantom load and usage times of various appliances and electronics were sourced from the Government of Canada and Lawrence Berkley National Laboratory [21, 22].

Energy savings per smart plug:

- 1 smart plug (TV, cable box, sound system) reduces electricity consumption by 236 kWh (2.6%) per year.

- 2nd smart plug (TV, cable Box, laptop charger) reduces electricity consumption by 206 kWh (2.3%) per year.
 - Combined, two smart plugs result in 442 kWh (5%) per year in electricity savings.
- With electronics and appliances making up about 18% of household electricity consumption according to Hydro Quebec, this equates to 1620 kWh based on a total household energy consumption of about 9000 kWh according to OEB. As a result, these two smart plugs result in a 27% savings in electricity consumption from appliances and electronics.
- 3rd smart plug connect with microwave and reduces electricity consumption by 43 kWh/year.
- 4th smart plug connects coffee maker and blender and reduces electricity consumption by 10 kWh/year.
- 5th smart plug connects printer and LCD monitor and reduces electricity consumption by ~50 kWh/year.
 - The combined five smart plugs result in a reduction of 545 kWh (6%) in electricity consumption.

Energy consumption of smart devices

The following is the energy consumption required to operate the smart home devices.

- Phillips Hue Hub: 2 W continuous = 17.5 kWh/yr
- Samsung Hub: 2 W = 17.7 kWh/yr
- Ecobee Thermostat: 1 W continuous = 8.8 kWh/yr
- Window Contact sensors: Battery operated, battery replaced once per year

- Motion Sensor: Battery operated, battery replaced once per year
- Smart plugs: $1 \text{ W/plug continuous} = 8.8 \text{ kWh/plug/yr} \times 4 \text{ plugs} = 35 \text{ kWh/yr}$

Therefore the additional energy consumption as a result of smart devices is around 80 kWh/yr.

Electricity savings from real-time consumption feedback

Appliance and electronic level feedback:

- Based on a report by Stanford University [18] and pilot done by Hydro One in Ontario [13], the estimated energy savings from real-time appliance level feedback and more detailed savings recommendations to occupants is between 10% and 12%. With annual electricity consumption stated as 9000 kWh by OEB for the average residence, savings would be around 1000 kWh.

Unit level feedback:

- Based on a pilot done by Hydro One in Ontario [13], the estimated energy savings for real-time unit level feedback to occupants is 6.5%. With annual electricity consumption stated as 9000 kWh by OEB for the average residence, savings would be around 580 kWh.

Hot water energy and water consumption savings from showering

Based on a study from the Swiss Federal Office of Energy (SFOE), the Amphiro shower metering solution has been confirmed to deliver an average savings of 215 kWh/person,

which has been confirmed in 3,000 households to date [9]. With units modelled as containing 2 occupants, this equates to a savings of 430 kWh.

With one source stating that the average household uses 2000 kWh/year for hot water heating [9], and considering that the OEB has stated that the average Ontario residence consumes about 9000 kWh/year in electricity, this is just over 20% of household electricity consumption. Hydro Quebec backs this up by stating hot water consumption makes up 20% of household electricity use. The Amphiro shower meter provides about 21% savings on hot water energy consumption. In terms of water, this is about 8500 L (2250 gallons). This equates to 4.8% savings on entire household electricity consumption (430 kWh/9000 kWh).

Table 10.1 outlines the general methodology taken for obtaining the energy savings potential of each of the sensors and control points selected for the smart home energy system.

Table 10.1: Methodology for obtaining energy savings and cost of each sensor, meter and control point

Sensor/Meter/Controller	Methodology for Potential Energy Savings	Cost
Programmable thermostat - Setups and setbacks	A research study conducted by Natural Resources Canada on the effects of setups and setbacks in an R2000 test home, found that 10-13% savings on heating energy and 11% savings on cooling energy would be obtained [17]. Using modelled energy consumption data for heating and cooling condo units, the estimated savings in kWh could then be determined.	The cost of an average programmable thermostat was taken from a Honeywell model. See Table 6.1 for details.
Programmable thermostat - Set-point	Using actual temperature set-point data of Canadian households provided by the 2011 SHEU report (Survey of Household Energy Use report), lower temperature set-points were validated to achieve potential energy savings [20].	Same as above.

Smart thermostat - Setups and setbacks	Estimated savings were obtained from Nest research studies on users with Nest thermostats. It was found that on average their smart thermostats result in 10% heating energy savings and 15% cooling energy savings [12].	Cost of an average smart thermostats was taken from a Nest model. See Table 6.1 for details.
Smart thermostat - Set-Point	See above in “programmable thermostat – set-point” description.	Same as above.
Smart plugs	Savings from smart plugs were estimated by calculating the amount of time the electronics plugged into them would spend in standby mode, and then calculating what the phantom loads for those electronics would be during that time. These loads would be eliminated by virtue of the fact that smart plugs would allow occupants to easily unplug those electronics.	Cost of these smart plugs was taken from two suppliers, Wemo. Details of which can be found in Table 6.1.
Real-time energy consumption feedback – Unit level meter	Based on a pilot done by Hydro One in Ontario [13], the estimated energy savings for real-time unit level feedback to occupants is 6.5%. With annual electricity consumption stated as 9000 kWh by OEB for the average residence, savings would be around 580 kWh.	Cost for a compliance standard, unit level meter was provided by QMC Meters. See Table 6.1 for more details.
Real-time energy consumption feedback – Appliance level meter	Based on a report by Stanford University [18] and pilot done by Hydro One in Ontario [13], the estimated energy savings for real-time appliance level feedback and more detailed savings recommendations to occupants is between 10% and 12%.	Cost for an appliance level electricity meter was taken from a company called SENSE. See Table 6.1 for more details.
Hot water from showering (Amphiro model)	Based on a study by the Swiss Federal Office of Energy (SFOE), the Amphiro shower metering solution has been confirmed to deliver an average savings of 215 kWh/person, which has been confirmed in 3,000 households to date [8]. With units modelled as containing 2 occupants, this equates to a savings of 430 kWh.	The cost of these hot water shower meters was taken from the Amphiro website. More details found in Table 6.1.

Simple payback of metering and controls packages

Table 10.2 below provides a summary of how the payback period for the smart home energy system was calculated.

Table 10.2: Simple payback period for metering and controls packages (Ontario)*

Metering and Controls Package	Cost	Annual Savings (per unit)	Payback Period (WOI)²	Payback Period (WI)^{1,3}
Bronze Package	\$1150	\$0.1/kWh*1170 kWh = \$117	9 years	18 years
Silver Package	\$1250	\$0.1/kWh*2000 kWh = \$200	6 years	12 years
Gold Package	\$1375	\$0.1/kWh*2400 kWh = \$240	5.5 years	11 years
Platinum Package	\$1650	\$0.1/kWh*2550 kWh = \$255	6.5 years	13 years

*Price of electricity is an average (10 cents/kWh) of the Ontario time of use rates.

¹WI = With Installation Costs included

²WOI = Without Installation Costs included

³Cost of packages with installation is assumed to be double the cost of the package without installation

Modelling methodology of energy savings potential for various home energy systems

Table 10.3 and 10.4 provide the methodology for modeling the energy systems analyzed in Chapter 4.

Table 10.3: Energy consumption potential for various unit level systems from occupant faults

Case Type	Modelling Description	kWh/1500 condo units/yr*	Annual Equivalency
Window used for fresh air intake	Effect of windows slightly open for fresh air (2 hrs in evenings when occupants arrive from work).	652,200	Electricity use of 60 Canadian homes (11,000 kWh per household)
Electric heater use	Supplemental heating from portable electric heater (4 hrs/day during winter months)	810,000	Electricity use of 74 Canadian homes
Lights high – faults resulting in high energy use	Lights being left on (assuming LED bulbs) – high case.	126,140	Electricity use of 11 Canadian Homes
Lights low– faults resulting in low energy use	Lights being left on (assuming LED bulbs) – low case.	25,200	Electricity use of 2.5 Canadian homes

Electronics left on	Electronics left on (computer display, digital cable box, audio system, and printer) during 16 hours of non-use times (asleep and at work).	792,820	Electricity use of 72 Canadian homes
		Gallons/Zibi/yr	Annual Equivalency
Brushing teeth & water running (2.2 gpm)	Leaving water running while brushing teeth (2 min twice a day).	7,708,800	Drinking water for the town of Collingwood (22,000 people)
Brushing teeth & water running (1.5 gpm)		5,256,000	30% reduction in water use

*1500 condos is the amount of units in the industry partners residential development

Table 10.4: Energy savings potential for various unit level systems from occupant behaviour

Case Type	Modelling Description	kWh/1500 condo units/yr*	Annual Equivalency
Heating and cooling set-point	Energy savings were calculated by comparing the energy consumption from high temperature set-points to low temperature setpoints based on actual temperature setpoint data from Natural Resources Canada.	1,380,000	Electricity consumption of 125 Canadian homes
Weekend temperature setback	Setting temperature to 16 deg. in winter and 28 deg. in summer (assume 4 weekend getaways per year).	52,820	Electricity use of 5 Canadian homes
Blind use	Energy savings were calculated by comparing the heating and cooling energy consumption for the unit with (closed when in cooling mode and high solar irradiance) and without blind use.	22,000	Electricity consumption for 2 homes
Water heating	Water heating energy savings were calculated by comparing the energy consumption of various shower lengths and shower head flow rates.	1,497,600	Electricity consumption for 136 Canadian homes

Natural cooling	The energy savings from natural cooling were determined by comparing the unit cooling energy consumption with and without natural cooling. Natural cooling was modelled as windows being opened whenever temperature data showed outdoor temperatures to be less than the desired indoor temperature (temperature set-point) during cooling season.	528,000	Electricity consumption of 47 Canadian homes
Dishwasher	Energy saving were modelled by modelling different types of appliance usage patterns.	240,000 – 300,000	Electricity consumption of around 24 Canadian homes
Dryer	Energy saving were modelled by modelling different types of appliance usage patterns.	636,000 – 1,021,000	Electricity consumption of 60 - 90 homes
Washer	Energy saving were modelled by modelling different types of appliance usage patterns.	60,000 – 98,400	Electricity consumption of 5 – 10 Canadian homes
Electronics	Electronics were modelled as off for an average of 20 hours in the day. This was backed by research findings from NRCAN.	690,000	Electricity consumption of 63 Canadian homes

*1500 condos is the amount of units in the industry partners residential development

Modelling specifications

North and South side units were modelled based upon specifications for the Windmill Developments Zibi Block 13 building along with industry standard operating values. This included a ventilation rate of 20 L/s, infiltration of 5.7 L/s, as well as total daily internal heat gains of 6.2 kWh. Heating and cooling systems were modelled with ideal systems that can provide exactly the heating and cooling rate required to achieve the heating season temperature set-points (21°C daytime and 18°C nighttime) and cooling

season set-point (24°C). Table 10.5 below outlines the specifications for the units that were modelled in Chapter 4 and Table 10.6 outlines the required ventilation rates for various room types in order to determine the entire unit ventilation capacity.

Table 10.5: North and South unit specifications[24]

Specification Type	South Side Specifications	North Side Specifications
Window shading coefficient	0.35	0.35
Window SHGC	0.30	0.30
Window U-value	0.33 Btu/hr-ft ² °F (1.87 W/m ² K)	0.33 Btu/hr-ft ² °F (1.87 W/m ² K)
Window to wall ratio (WWR)	40%	40%
Window visible transmittance	0.8	0.8
Window frame U-value (aluminum)	0.88 Btu/hr-ft ² °F (5 W/m ² K)	0.88 Btu/hr-ft ² °F (5 W/m ² K)
Balcony	6 ft. deep (wall to edge), 100% of wall width	6 ft. deep (wall to edge), cover 50% of North side windows
Wall U-value	0.059 Btu/hr-ft ² °F (0.33 W/m ² K)	0.059 Btu/hr-ft ² °F (0.33 W/m ² K)
Roof R-value	(31 hr-ft ² °F/Btu) (5.5 m ² K/W)	(31 hr-ft ² °F/Btu) (5.5 m ² K/W)

Ventilation Rate

The ventilation rate for the units was based on a typical unit with 1 master bedroom, 1 bedroom, 2 baths, 1 kitchen, 1 living room, 1 office, and 1 laundry area. This resulted in modelling the units with a ventilation rate of about 40 L/s and an HRV with an effectiveness of 50%. Table 10.6 below shows the required ventilation capacity for different building spaces.

Table 10.6: Ventilation capacity [23]

Room	Capacity (L/s)
Master bedroom	10
Other bedrooms	5
Living room	5

Dining Room	5
Family Room	5
Recreation Room	5
Kitchen	5
Bathroom	5
Laundry/Utility Room	5

2050 weather file for modelling

The units were modelled using predicted weather data for the year 2050. As shown in Table 10.7, the HDD and CDD differs between our current weather (2020) and future weather (2050).

Table 10.7: Weather file heating and cooling degree days

	2020 weather file	2050 weather file
Heating Degree Days (HDD)	4730	4345
Cooling Degree Days (CDD)	250	425

Unit space and footprint

Modelled condos are based on 100 m² floor area and a square floor plan as most of the condos are relatively square [24]. This represents the conservative case because of greater exposure of walls to the outdoor environment.

Internal heat gains

ASHRAE Standard 90.2-2007 was used to base average internal heat gains for each of the units. This considers heat gains from lights, people and equipment and is based on specifications outlined by ASHRAE 90.2-2007 [25].

Internal heat gains of 6.2 kWh/day were determined based on ASHRAE internal heat gain specifications and used for modelling. Calculations can be found below.

$$20,000 \text{ Btu/day} = 5.86 \text{ kWh/day}$$

$$15 \text{ Btu}/(\text{day} \cdot \text{ft}^2) = 0.00315 \text{ kWh}/(\text{m}^2 \cdot \text{day}) = 0.315 \text{ kWh/day for } 100 \text{ m}^2 \text{ unit}$$

So total daily internal heat gains = **6.2 kWh**

Infiltration

The Infiltration rate for the units was determined to be 5.7 L/s. This is based on a standard infiltration rate of 0.3 CFM₅₀/ft² which was adjusted for increased pressure differences across the building envelope at higher elevated units [26, 27].

The calculations for obtaining the infiltration rate can be seen below.

$$\text{Infiltration rate assumed} = 3 * 0.3 \text{ CFM}/\text{ft}^2 * 270 \text{ ft}^2 * 1/20 * 0.47 \text{ L/s}/\text{CFM} = \mathbf{5.7 \text{ L/s.}}$$

Basis for bronze back-end controls and metering package

Figure 10.1 is a letter from Windmill Developments outlining their planned metering package for their residential units. Windmill Developments was the industry partner on this research study.

As part of the District Thermal Heating and Cooling System (implemented and operated in partnership with Hydro Ottawa), an elaborate energy sub-metering strategy will be employed in order to allow for consumption billing as well as providing real-time feedback as part of a “user experience”.

The “user experience” will involve real-time energy consumption information and conservation guidance provided on a suite level interface along with the provision for a mobile application.

Suite/Unit metering for Zibi Ottawa will consist of the following:

- Heating and Conditioning Thermal Energy;
- Domestic Hot Water Consumption;
- Potable Water Consumption (commercial food services spaces); and
- Electricity Consumption (meter provided by Hydro Ottawa).

Suite/Unit metering for Zibi Gatineau will consist of the following:

- Domestic Hot Water Consumption;
- Potable Water Consumption (commercial food services spaces); and
- Electricity Consumption (meter provided by Hydro Quebec).
- Please do not hesitate to contact the undersigned if you wish to discuss the matter further.

Figure 10.1: Utility Sub-Metering Strategy for Zibi – February 8, 2016 letter from Windmill Developments [24]

10.2. Appendix B – Chapter 7

Tables 10.8 and 10.9 show the energy consumption breakdown for all of the phantom loads in the detached home and condo unit.

Table 10.8: Phantom load energy breakdown for detached home

Source	Phantom load (W)	Hours consuming phantom load (off or standby)	Hours that device could be cut off from power	Annual phantom load energy consumption (kWh)	Annual phantom load energy consumption that can be eliminated (kWh)
Coffee maker	1.5	23.5	23.5	13	13
Microwave	2	23.9	23.9	17	0
Philips hub	2	7	7	18	18
Samsung hub	1	7	7	9	9
Wireless routers	12	7	7	105	105
Wii	8	23.5	23.5	69	69
Speaker system 1 (home office)	6	23	23	50	50
Speaker system 2 (bedroom desk)	3	23.9	23.9	26	26
Speaker system 3 (living room)	3	23.9	23.9	26	26
Oven	3	23	0	25	0
TV	1	23.5	23.5	9	9
Printer (Laser)	2	23.95	23.95	17	17
Smartphone 1 charger	1	10	10	4	4
Smartphone 2 charger	1	10	10	4	4
Laptop 1 Charger	1	4	4	2	2
Laptop 2 Charger	1	6	6	2	2

Smartphone 1 plugged in, sleeping, charged		6	6		
Smartphone 2 plugged in, sleeping, charged		6	6		
Laptop 1 plugged in, sleeping, charged	2	10	10	7	7
Laptop 2 plugged in, sleeping, charged	2	10	10	7	7
Total				317	274

Table 10.9: Phantom load energy breakdown for condo unit

Source	Phantom load	Hours off or on standby consuming phantom load	Hours that device could be cut off from power	Total phantom load energy consumption	Phantom load energy consumption that can be eliminated
Coffee maker	1.5	23.5	23.5	13	13
Microwave	2	23.9	0	17	17
Philips hub	2	7	7	18	18
Samsung hub	1	7	7	9	9
Wireless routers	6	7	7	105	105
Wii	8	23.5	23.5	69	69
Speaker system 1 (home office)	3	23	23	50	50
Speaker system 2 (bedroom desk)	-	-	-	-	-
Speaker system 3 (living room)	3	23.9	23.9	26	26
Oven	3	23	0	25	0
TV	1	23.5	23.5	9	9

Printer (Laser)	-	-	-	-	-
Smartphone 1 charger	1	10	10	4	4
Smartphone 2 charger	1	10	10	4	4
Laptop 1 Charger	1	4	4	2	2
Laptop 2 Charger	1	6	6	2	2
Smartphone 1 plugged in, sleeping, charged		6	6		
Smartphone 2 plugged in, sleeping, charged		6	6		
Laptop 1 plugged in, sleeping, charged	2	10	10	7	7
Laptop 2 plugged in, sleeping, charged	2	10	10	7	7
Total				250	190

Figure 10.2 shows a snapshot of the smart plug interface which is showing the phantom load of the electronics from the living room of the detached home.

Figure 10.2: Smart plug user interface showing phantom load of living room electronics

Day in the life of a smart home energy system occupant

The following outlines the day of an occupant living in a condo unit with a smart home energy system.

Jonathan wakes up at 7AM to start his day. He hops out of bed, grabs his towel and goes for a shower. While showering, Jonathans shower meter tells him how long he has been showering, and the amount of water and energy he is using. He finishes up his shower in 4 minutes, half the time of the average Canadian! This is because the real-time feedback from his shower meter incentivizes him to keep his showers shorter to conserve energy and water. Jonny finishes getting ready and leaves for work. However, because he was in such a rush he forgets to turn the lights off in his bedroom and bathroom. Thankfully his smart home system senses that he has left and not only turns the lights off, but also turns

off all the phantom loads and sets the thermostat cooling set-point up from 24°C to 27°C to conserve cooling energy. Jonny is able to remotely turn off the lights from his smart phone while on the bus to work. The phantom load reductions include savings from his sound systems, cable box, TVs, game console, coffee maker, and printer.

During the workday, Jonathans apartment has heated up to 25°C due to solar gains, and requires cooling before he arrives home. The smart home energy system has learned Jonathans weekly schedule and starts cooling at 4:30pm for his 5pm arrival. The outdoor air is at a temperature of 18°C and is available to provide natural cooling. Instead of using mechanical cooling, the smart system activates the HRV bypass unit and brings the outdoor air inside to cool the space back down to 24°C. This has saved Jonathan energy and money on cooling and the smart system makes note of this on the user interface for Jonathan to see when he has time. At 10pm Jonathan starts getting ready for bed when his smart system provides him with a notification that his refrigerator and stove are using more energy than expected and suspects that the refrigerator door might have been left open and stove element left on. He checks the kitchen and sure enough he has left the stove element on and refrigerator door slightly ajar. He corrects the problem and heads to bed at 11pm. The smart system senses that there is no movement in the condo anymore and turns all the lights off in the home. At 12AM the smart home system acts based on a schedule created by the smart thermostat sensors and automatically shuts off the phantom loads to all appliances in the suite. While sleeping, Jonathans smart home energy system utilizes natural cooling though the HRV to maintain a comfortable indoor air temperature.

At the end of the week, Jonathans smart system provides him a breakdown of how much energy he has saved and where he ranks against other occupants in his condo building. Monthly, weekly, daily and appliance/system level energy usage breakdowns for his suite are available for his viewing 24/7, and can provide him information about the most energy intensive systems and occurrences, and how his energy efficiency is progressing. It will also provide him suggestions as to how he should go about improving his energy efficiency within his home based on his previous weeks energy consumption.

10.3. Appendix C – Chapter 8

Figure 10.3 shows a line plot of the indoor and outdoor temperatures on an hourly basis throughout the year. It helps to depict just how much natural cooling potential there is, even during the summer months, if it can be utilized effectively.

Figure 10.3: Indoor vs outdoor temperature for modelled apartment unit

The following items were considered and included in the calculations for determining the energy and cost savings from natural cooling using an ERV bypass.

10.3.1. Natural Cooling Available

The following steps were used to determine the natural cooling energy available to offset cooling loads at any given hour throughout the year.

Step 1: Use Equation 10.1 with the following variables to determine the cooling energy available during a specific hour throughout the year. Density of air was constant at 1.225 kg/m³ based on standard temperature (15°C) and pressure (101.3 kPa). The specific heat

capacity of air was held constant for all calculations at 1.006 KJ/kg K corresponding to an air temperature of between 10°C and 20°C . Both the density and specific heat capacity were assumed constant as natural cooling was required the most during times when outdoor temperatures were between 10°C and 20°C which corresponds very close to the average air temperature for which these variables were taken at.

$$Q = MC\Delta T = \rho VC\Delta T \quad (\text{Equation 10.1})$$

- ρ : Density of air - 1.225 kg/m³
- C: Specific Heat Capacity of air – 1.006 KJ/kg K)
- Q: Heating or Cooling Energy - KJ/h
- V: Volumetric Flow Rate - m³/h
- M: Mass Flow Rate - kg/h
- ΔT : The temperature difference between 2 points (K)
 - $\Delta T = T_{\text{inside, setpoint}} - (T_{\text{out}} + ((1 - \text{fan efficiency} \times Q)/M \times C))$
 - $\Delta T = T_{\text{inside, setpoint}} - (T_{\text{out}} + (((1 - \text{fan efficiency}) \times P) \times (3.6 \text{ watts})/(1 \text{ KJ/h}))/M \times C$

ERV unit and temperature characteristics for example calculation:

- Unit: HOLTOP ERV 1.5 (XHBQ-D1.5DCTPA)
 - V: Volumetric Flow Rate = 150 m³/h
 - P: Power = 26 Watts
 - Assume motor is 80% efficient (20% of energy turns into heat)
- Day: May 20th (1pm-2pm), $T_{\text{out}} = 13^\circ\text{C}$, $T_{\text{inside, setpoint}} = 22^\circ\text{C}$

$$Q = 1.225 \times 150 \times 1.003 \times (22 - ((1 - 0.8) \times 26 \times 3.6 / (1.225 \times 150 \times 1.003)))$$

$$\underline{Q = 1658.71 \text{ KJ/h}}$$

Step 2: Find Q in Watts

$$Q = 1658.71 \text{ KJ/h} \times (1 \text{ Watt}/3.6 \text{ KJ/h})$$

$$Q = 461 \text{ Watts}$$

Step 3: Compare with cooling energy required

Q required by condo unit is only 380 watts, therefore the 461 watts of natural cooling available through the ERV bypass is able to meet this cooling requirements and the amount of cooling energy offset for this hour of the year is 380 Wh.

10.3.2. Fan Energy Consumption

To bring the outdoor air into the indoor environment (apartment unit) a fan is used as part of the ERV bypass unit. The fan energy consumption was determined to ensure that proper energy accounting was done during this analysis. It needed to be subtracted from the final energy savings amount to determine the net energy savings possible from natural cooling provided by an ERV bypass. The following steps were taken to account for fan energy consumption:

Step 4: Based on the 380 Wh of energy required to meet the cooling load of the condo unit for the one hour of the day analyzed above, Equation 10.1 was used to determine what the flow rate of the ERV would need to be in order to provide that cooling energy from outdoor air.

$$V = Q/\rho C\Delta T = 380 \times ((3.6\text{KJ/h}/ 1 \text{ Watt})/ 1.225) \times 1.003 \times 9$$

$$V = 124 \text{ m}^3/\text{h}$$

Step 5: Utilizing fan law equations for a centrifugal fan with a constant diameter, the power required by the ERV fan for the required flow rate can be determined as follows.

$$P_1/P_2 = (n_1/n_2)^3 = (q_1/q_2)^3 \quad \text{(Equation 10.2) [6, 7]}$$

- P = Power of fan
- n = Fan speed
- q = Volume flow capacity

$$P_2 = P_1/(q_1/q_2)^3 = 26 \text{ watts}/((150 \text{ m}^3/\text{h})/(124 \text{ m}^3/\text{h}))^3$$

$$\underline{P_2 = 15 \text{ watts}}$$

10.3.3. Total Cooling Energy and Cost Savings

Next, cooling energy savings were organized by what time of the day that they occurred (off-peak, mid-peak, or on-peak hours), based on Ontario Hydro time of use pricing.

Step 6: The cooling energy savings, cooling energy requirements, as well as fan energy requirements for all hours of the year (8760 hours) were added up based on what time of day they occurred (off-peak, mid-peak, or on-peak hours of the day).

Step 7: The total energy savings were subtracted by the total fan energy requirements for each of the time periods to get the net cooling energy savings achieved.

Step 8: Each net subtotal of energy savings in the different time periods (off-peak, mid-peak, and on-peak) were then multiplied by their time of use pricing rate. This gave the amount of cost savings achieved during that usage period over the course of a year.

Step 9: All the energy savings and cost savings from the winter and summer time-of-use subtotals were added up to get the annual energy and cost savings

10.3.4. Analysis of Outdoor Humidity Levels

Natural cooling energy savings were only calculated during times that outdoor humidity levels were in an acceptable range as to not increase indoor humidity levels above an acceptable level. This was done to ensure that natural cooling does not add any burden on

the mechanical heating and cooling system to dehumidify the air, which would only require energy and defeat the purpose of using natural cooling in the first place.

The upper limit that was allowed for the indoor humidity was 60% RH at 24°C, which results in an absolute humidity level of about 0.013 kg of water vapour/m³ of air. Using this as the upper limit, the absolute humidity levels were calculated for each hour of the year to determine whether natural cooling could be used during this hour without increasing indoor humidity levels. The equations used can be found below:

$$A = C \times (P_w/T) \quad (\text{Equation 10.3})$$

- A = Absolute Humidity (kg/m³)
- C = Constant (2.16679 kgK/KJ)
- P_w = Vapour Pressure (kPa)
- T = Air Temperature (K)

$$P_w = P_{ws}(T) \times (\%RH/100) \quad (\text{Equation 10.4})$$

- P_{ws}(T) = Saturation Vapour Pressure (kPa). See Table 8.5 for the saturation vapour pressures used for various temperature ranges.
- %RH = Relative Humidity at Temperature for which absolute humidity is being calculated for.

Table 10.10: Saturation vapour pressure for various air temperatures.

Temperature	Water Saturation Pressure	
[°C]	[kPa]	[psi]
0.01	0.6116	0.0887
2	0.7059	0.1024
4	0.8135	0.1180
10	1.2282	0.1781
14	1.5590	0.2319
18	2.0647	0.2994
20	2.3393	0.3392
25	3.1699	0.4597
30	4.2470	0.6159
34	5.3251	0.7723
40	7.3849	1.0711
44	9.1124	1.3216