FINANCIAL INCENTIVES FOR GREEN BUILDINGS IN CANADA: A SPATIO-TEMPORAL ANALYSIS

by

Anber Rana

M.Sc. Eng., University of Engineering and Technology, Lahore, 2012
B.Sc. Eng., University of Engineering and Technology, Lahore, 2008

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

DOCTOR OF PHILOSOPHY

in

THE COLLEGE OF GRADUATE STUDIES

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA
(Okanagan)

August 2021

The following individuals certify that they have read and recommend to the College of Graduate Studies for acceptance, the dissertation entitled:

Financial Incentives for Green Buildings in Canada: A Spatio-temporal Analysis

submitted by Anber Rana

in partial fulfillment of the requirements for

the degree of Doctor of Philosophy

Examining Committee:

Dr. Rehan Sadiq, School of Engineering
Supervisor

Dr. Kasun N. Hewage, School of Engineering
Co-supervisor

Dr. Shahria M. Alam, School of Engineering
Co-supervisor

Dr. Sumi Siddiqua, School of Engineering
Supervisory Committee Member

Dr. Sepideh Pakpour, School of Engineering
Supervisory Committee Member

Dr. Ahmad Rteil, School of Engineering
Supervisory Committee Member

Dr. Nathan Pelletier, Faculty of Management
University Examiner

Dr. Thomas Froese, Department of Civil Engineering, University of Victoria
External Examiner

Abstract

Green buildings (GBs) are considered to be a more cost-effective and viable solution than transport and other industry sectors to attain carbon mitigation targets. To promote the large-scale adaptation of GBs, one of the key "on-ground efforts" from the government include the development of appropriate financial incentives (FIs). Keeping in view the diverse scope and scale of FIs, an evaluation of FIs is critically important to increase the rate of construction of GBs and to meet desired mitigation targets. The evaluation of FIs involves consideration of the complex nature of building, stakeholders' perspectives and spatio-temporal design and economic parameters that are rarely considered in conventional studies. Hence, there is a need for pragmatic decision-making that will help in making FIs planning that is beneficial to all stakeholders.

In order to address, this need, the main objective of this research is to develop a decision support framework that can evaluate the effectiveness and efficiency of FIs available for GBs in Canada. This objective was achieved in five distinct steps. First, the research reviewed the existing status of FIs in Canada and the techniques used to evaluate FIs, which helped to identify knowledge gaps and specific research requirements in this area. The second step determined the impact of occupancy profiles of residential buildings on estimating viable energy-saving measures. The third step investigated the effectiveness of available FIs for a range of design and economic parameters. The fourth step evaluated the efficiency of available FIs for single buildings and neighborhoods from private and government perspectives. The last step investigated the environmental impacts of operation strategies of a public building and trade-offs between human health and their implication on eligible FIs.

The framework presents realistic impacts of the variability in occupancy, operation, building archetypes, stakeholders perspectives, location and economic parameters on effectiveness and efficiency of incentive policies. The results obtained have the potential to be used by investors and policymakers to increase GBs and achieve sustainable neighborhoods by providing an evaluation method. The policy recommendations can help design and allocate FIs to areas that will yield the largest benefits for all stakeholders.

Lay Summary

Green buildings (GBs) offer a viable solution to address the problem of carbon mitigation; however, in practice, the rate of construction of GBs is restricted due to various reasons, such as high initial costs and longer construction times. Therefore, governments are offering financial incentives (FIs) such as rebates, taxes, loans to promote large-scale construction of GBs. These FIs need to be carefully evaluated to gain maximum carbon reduction. The main goal of this research is to provide a decision support framework that evaluates the performance of existing FIs in Canada. The framework generates realistic solutions by considering building design and economic parameters. Results obtained from this research have the potential to improve current FIs planning to attain high environmental and cost benefits. This research will be useful for building owners, managers, developers, local utility and municipality and policy makers to make informed decisions for obtaining GBs and sustainable neighborhoods.

Preface

I, Anber Rana, ideated, matured, developed and wrote this thesis under the supervision of Drs. Rehan Sadiq, Kasun Hewage and Shahria Alam. Five journal articles, two conference proceedings and one poster presentation, which are currently published, accepted, or under review, have been prepared directly or indirectly from the research presented in this thesis. The first journal paper focused on the review of financial incentives for green buildings in Canada and methods used for evaluating financial incentives. The second article explored the impacts of occupancy profile on residential building energy end-use, while the third article focused on the impacts of operational management strategies in public swimming pool facilities. The fourth article estimated the effectiveness of FIs for residential archetypes and studied their sensitivity with respect to location, design and economic factors. The fifth paper evaluated the efficiency of the existing FIs' policy from government and end-user's perspectives. In addition to these, two conference articles and poster presentation related to this research were also published.

Journal Articles (Published)

1. **Rana, A.**, Sadiq, R., Alam, M.S., Karunathilake, H., Hewage, K., 2021. Evaluation of financial incentives for green buildings in Canadian landscape. *Renewable and Sustainable Energy Reviews* (Elsevier). https://doi.org/10.1016/j.rser.2020.110199
2. **Rana, A.**, Perera, P., Ruparathna, R., Karunathilake, H., Hewage, K., Alam, M.S., Sadiq, R., 2020b. Occupant-based energy upgrades selection for Canadian residential buildings based on field energy data and calibrated simulations. *Journal of Cleaner Production* (Elsevier). https://doi.org/10.1016/j.jclepro.2020.122430
3. **Rana, A.**, Dyck, R., Hu, G., Hewage, K., Rodriguez, M.J., Alam, M.S., Sadiq, R., 2020a. A process-based LCA for selection of low-impact DBPs control strategy for indoor swimming pool operation. *Journal of Cleaner Production* (Elsevier) 270. https://doi.org/10.1016/j.jclepro.2020.122372

Journal Articles (Under Preparation)

4. **Rana, A.**, Hewage, K., Alam, M.S., Karunathilake, H., Sadiq, R., Financial Incentives for new residential buildings in Canada: Investigating effectiveness using sensitivity analysis. (Expected to be submitted to *Applied Energy* (Elsevier) in August 2021)

5. **Rana, A.**, Hewage, K., Alam, M.S., Sadiq, R., Rebates Efficiency at Building and Neighborhood level. (Expected to be submitted to *Journal of Cleaner Production* (Elsevier) in September 2021)

Conference Proceedings

6. **Rana, A.,** Alam, M.S., Hewage, K., Sadiq, R., "Evaluation of financial incentives on renewable energy technologies used in residential buildings in Canada", 5th Annual Engineering Graduate Symposium (AEGS-2019), Kelowna, British Columbia, Canada, 02nd February 2019. https://csce.ca/elf/apps/CONFERENCEVIEWER/conferences/2017/pdfs/CONSPEC/FinalPaper_59.pdf
7. **Rana, A.,** Alam, M. S., Charles, K., Perera, P., Hewage, K., Sadiq, R., Thermal transmittance values for double and triple glazed windows: experimental results from lab and in-situ measurements, 1st International Conference on New Horizons in Green Civil Engineering (NHICE-01), Victoria, British Columbia, Canada, 25-27th April, 2018. https://onlineacademiccommunity.uvic.ca/nhice/wp-content/uploads/sites/2382/2019/02/Proceedings_22Feb2019.pdf

Poster Presentations:

8. **Rana, A.,** Hewage, K., Alam, M.S., Sadiq, R., Financial Incentives for Green Buildings-A Scientometric Analysis", Poster presentation at 1st UBCO Inaugural Cluster Trainee Poster Session, Kelowna, British Columbia, Canada, 25th February 2020.

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List of Abbreviations

AB	Alberta
AHU	Air handling units
APP	Appliances upgrade
ATH	Advance tech home
BC	British Columbia
BC-ESC	British Columbia Energy Step Code
BEC	Building energy codes
BEopt	Building Energy Optimization Tool
BES	Building energy simulation
CAC	Command and Control
CCR	Charnes, Cooper & Rhodes
CIMS	Canadian Integrated Modelling System
CMHC	Canada Mortgage and Housing Corporation
CZ	Climate Zones
DBPs	Disinfection by-products
DEA	Data Envelope Analysis
DHW	Domestic hot water upgrade
dLL_{30}	Change in life cycle cost over 30-year period
DMUs	Decision making units
DSM	Demand-Side Management
EERE	Energy Efficiency and Renewable Energy
EPCs	Energy Performance Upgrades

FI	Financial Incentives
FN	Foundation wall upgrade
GB	Green Building
GHG	Greenhouse gas emission
GHGI	Greenhouse gas emission intensity
GM	Grey Model
HAA	Haloacetic acids
HDD	Heating Degree-Days
HELP	Home Energy Low-Income
HVAC	Heating Ventilation and Air Conditioning
IC	Initial capital costs
ICF	Insulating concrete foam
IEA	International Energy Agency
ILM	Intrusive load monitoring
IO-LCA	Input-output life cycle assessment
ISP	Indoor swimming pool
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life cycle inventory
LEAP	Long-range Energy Alternatives Planning
LED	Light emitting diode
LEED	Leadership in Energy and Environmental Design
LEV	Local exhaust vent

MARKAL	Market Allocation
MB	Manitoba
MBE	Mean Bias Error
MBI	Market-based Instruments
MCDM	Multi-criteria decision making
MEUI	Mechanical Energy Use Intensity
MURB	Multi-unit Residential Building
NEMS	National Energy Modeling System
NPO	Non-profit organizations
NRCan	Natural Resources Canada
NS	Nova Scotia
NZEB	Net-Zero Energy Building
OB	Occupant behavior
ON	Ontario
PBP	Payback Period
PEI	Prince Edward Island
P-LCA	Process-based life cycle assessment
PV	Solar photovoltaic system
QC	Quebec
RECS	Residential Energy Consumption Survey
RF	Roof insulation upgrade
RMSE	Root Mean Square Error
RWH	Rainwater harvesting system

SFD	Single Family Detached Homes
STH	Standard home
TABULA	Typology Approach for Building Stock Energy Assessment database
TEDI	Thermal Energy Demand Intensity
THM	Trihalomethanes
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UBC	University of British Columbia
US	United States
UV	Ultravoilet treatment
WL	Wall insulation upgrade
WN	Window upgrade
WWR	Window-to-Wall Ratios

Acknowledgments

First and foremost, I would like to acknowledge the continuous support of my supervisor, Dr. Rehan Sadiq. Dr. Sadiq provided me with all the resources, guidance and freedom necessary to ensure success and happiness during my graduate studies. I would like to thank him for his patience and kindness that helped me develop confidence in my work, ability to conduct independent research and to grow professionally. I will be forever grateful to Dr. Sadiq for giving me the opportunity to work in such a diverse research group and for being a constant source of motivation.

I would also like to sincerely thank my co-supervisors, Dr. Kasun Hewage and Dr. M. Shahria Alam, for sharing their expertise and boundless knowledge as well as providing continuous guidance throughout the research process. Dr. Hewage and Dr. Alam were fundamental in helping me improve the quality of my work. This thesis would not have succeeded and reached the current form without their professional guidance and continuous encouragement.

I thankfully acknowledge Dr. Sumi Siddiqua, Dr. Ahmad Rteil and Dr. Sepideh Pakpour for serving as my supervisory committee members. I would also extend my thanks to the number of industry project partners with whom I was fortunate to work and develop a practical understanding of current problems in the construction of energy-efficient buildings. I would especially thank Karin-Eger Blenk (Wilden), Russ Foster (Wilden), Martin Blenk (Wilden), Scott Tyerman (Authentech Homes), Carol Suhan (FortisBC) and Russell Street (UBC, Vancouver). In addition, financial support from NSERC, Mitacs, Wilden and FortisBC was beneficial in my studies. In the same vein, I would like to thank UBCO staff, especially Shannon Hohl, Stephanie Oslund, Angela Perry, Ms. Brittaney, Ms. Tanya Chartrand, Amanda Brobbel and Barbara Sobol, for their immense support throughout my time at UBC.

The support I received from the project life cycle management laboratory and the research team has been enormous. I would especially like to thank Dr. Guangji Hu, Dr. Hirushie Karunathilake, Dr. Rajeev Ruparathna, Dr. Piyaruwan Perara and Roberta Dyck for their valuable inputs and expertise that helped me in improving the presentation of my research. I would also like to acknowledge Dr. Syed Asad Hussain, Dr. KH MD Nahiduzzaman and Dr. Gyan Chhipi-Shrestha who volunteered their advice in reviewing my thesis.

I would also like to acknowledge role of my previous teachers and mentors who encouraged the educational endeavors that helped me in achieving this milestone. In this respect, some noteworthy names are Dr. Mohammad Akram Tahir, Prof. Zia-ud-din Mian, Prof. Faiz Ahmad Chishti, Prof. Ahmad Saeed Sheikh, Dr. Tauseef Ahmad, Madam Sabri and Dr. Husnain Haider.

In addition, my friends Sadia Ishaq, Humera Ahmad and Humera Mughal were a constant source of support and helped me to get through the hardest of times. I have developed fond memories of my times at UBC thanks to the company of Sadia and Saba Saleem. My long talks with Sadia were especially helpful in developing interest in research not only in my own topic but the practical implications of inter-disciplinary research.

Finally, I would like to extend my sincerest gratitude to my loving parents for their love and prayers throughout my life. I would especially like to thank my mother who in spite of her extremely poor health allowed me to study abroad and complete this long journey. I will also commend my siblings, Dr. Mahwash Rana, Dr. Irfan Ahmad Rana and Rafia Rana, for their constant support and encouragement that helped me in closing this chapter of my life.

Dedication

Dedicated

To my Family, Friends and Mentors

Chapter 1 Introduction

1.1 The Challenge

Green buildings (GBs) are considered one of the most desirable solutions to the climate change challenges; because of their benefits to environment, society and economy [1]. There are multiple definitions of GBs in literature, but broadly GBs can be defined as the use of construction practices or processes that yield resource efficient high-performance buildings with low environmental impacts [2,3]. In this study, GBs refer to sustainable buildings with high energy efficiency, low emissions and high life cycle performance. In addition to low resource consumption, GBs are associated with better indoor air quality and employees' work productivity [4,5]. Given these advantages, the construction of GBs is encouraged by local and national governments around the world [6]. Despite the numerous advantages related to GBs, a number of challenges hinder their implementation. Major impediments are higher initial costs, longer construction times, inadequate information and relevant expertise, reluctance to adopt newer technologies, hidden costs and benefits, market failure and behavioral constraints [7–12]. The majority of the GBs advantages occur during the operation stage [13]; hence, developers for new buildings are hesitant in making GBs with high initial investments [14,15]. Despite the importance of GBs in addressing climate change, there remains a paucity of empirical evidence on the benefits of GBs construction [10]. Furthermore, uneven cost and benefits distribution among building stakeholders is a hurdle to GBs adoption [16]. These challenges need to be addressed by establishing their technical and economic viability so that local and national carbon mitigation targets are achieved.

Challenges related to GBs' adoption can be removed through properly designed and deployed government policy instruments. Among these instruments, financial incentives (FIs) have proved to be pivotal in promoting GBs [17–20]. FIs in the form of subsidies, rebates and disincentives are monetary support provided to achieve an energy efficient building stock [17,18,21]. FIs help remove barriers related to high up-front investment, mobilization of renovation practices, encouragement of private investments, penetration of innovative low-carbon technologies and implementing other policy instruments. FIs are particularly important in reducing risk perception, thus filling existing knowledge gaps, promoting GBs construction practices and diffusing emerging energy technologies [22]. Likewise, the role of FIs in the widespread adaptation of renewable energy technologies is well recognized [23,24]. Incentives can also change the developers' behavior through financial penalizing or rewarding and establishing business cases that ensure GBs viability [25].

The importance of FIs in achieving more sustainable buildings is well recognized in the existing literature. However, proper implementation of FIs is hindered by some challenges. First, FIs require the use of government resources to be directed towards energy efficiency improvement of building stock [26]. Since the government has limited financial resources, FIs are in competition with other community projects and need to be strategically designed and distributed among building archetypes to ensure maximum benefits [27]. Second, there is a need to consider the perspective of all stakeholders to achieve optimal solutions. For instance, the government perspective requires the adoption of energy performance upgrades (EPUs) that yield maximum greenhouse gas (GHG) reductions. At the same time, the investors are interested in meeting regulatory requirements at least costs [28]. These conflicting requirements need to be considered to yield satisfactory results for FIs implementation. Third, the evaluation of energy conservation policies, including FIs policies, are predominantly based on qualitative analysis and more extensive and detailed quantitative studies are needed to achieve better decision making [29–31]. “Effectiveness” is one of the most important criteria that quantitatively measures the outcomes and benefits of applied FIs. To date, limited studies have evaluated the effectiveness of FIs for GBs [16]. Moreover, there is a diversity and disparity in FIs evaluation process that varies with stakeholders perspective (Government, society, utility or end-users) [21]. “Efficiency” is another criterion that measures the quality of outputs obtained with invested resources [32]. Efficiency values are required for proper allocation of resources; however, most efficiency studies are based on surveys performed after a FI program has been deployed. Therefore, in order to promote GBs, there is a need for more systematic planning and deployment of FIs.

Despite the presence of widely available energy efficient technologies and improved sustainable practices, the energy use of the building sector continues to rise and the rate of construction of GBs still remains low. The increase is attributed to the rising population, changes in living patterns as more individuals are living alone and longer, and larger floor areas with rising heating and cooling load to meet thermal comfort requirements. In this regard, a scientific evidence-based strategy is needed for effective decision making that will help make FIs planning that yields maximum benefits for the stakeholders. Such a strategy would integrate and measure the economic and environmental impacts of FIs and offer credible results for stakeholders.

1.2 Research Gap

An extensive literature review of financial incentives for green buildings revealed a number of research gaps that need to be addressed:

Lifecycle thinking in GBs decision making: Desirable benefits of GBs can only be achieved if suitable sustainability decisions are performed. Economic, energy, environmental and social impacts need to be considered for these decisions [33]. Lifecycle thinking (LCT) approaches help to attain sustainability by providing viable solutions that ensure minimum wastage of resources [34]. Application of these approaches during early design stages can yield the highest benefits by assessing construction, operation, maintenance and end-of-life cycle costs, energy and emissions impacts [35]. Establishing the connection between LCT and decision making is a recognized challenge [36]. A disconnect between LCT and decision making makes it difficult to compare findings of different GBs studies. Focus on initial investment is a major challenge in adopting GBs and the use of lifecycle costs can yield benefits [10,14,37]. Furthermore, the literature reveals that the majority of the studies on energy efficiency are focused on cost-optimality with limited consideration of environmental and social impacts [38,39]. Hence, there is a need for a comprehensive evidence-based framework that considers LCT for decision making in GBs.

Impact of GBs operation on occupants' health and incentives: Changing building operation can decrease energy use and hence qualify the buildings for higher FIs [40]. In this regard, performance-based incentives for commercial and large buildings are particularly important. Interaction between human health and energy use of building is complex. A building operating at low-energy may adversely impact occupants' health due to an increase in indoor pollutants. Likewise, the use of LCT approaches for selecting the operation strategy should consider occupants' well-being for decision making [41]. However, existing literature has often selected processes or products ignoring the direct impacts on human health [42,43]. Similarly, studies considering the relationship between FIs for GBs and human health are rare and most concentrated on the impact of low carbon technology, such as replacement of stoves with wood pellets [44–46]. There is a need for a framework that can inform about the impact of change in building operation on incentives and human health. Hence, an integrated framework is required that can capture the impacts of decreased energy use on human health and the environment.

Impact of all building characteristics on FIs evaluation: Buildings have distinctive architectural characteristics, climate location and operational features that need to be rationally investigated for the selection of EPUs[47]. Hence, the selection of EPUs that yield desired energy and GHG reduction targets for a particular archetype is a complex process. Likewise, energy savings potential varies with archetype and will be higher in some projects compared to others [48]. Many studies on FIs effectiveness have considered either a single building archetype or the impact of a particular EPU [49–54]. Regional geography and climate variations do not allow for a universal GBs solution [54]. Existing frameworks have inadequately considered the influence of regional parameters in sustainable buildings design [55]. Similarly, in order to improve FIs, local conditions cannot be ignored [16]. Hence, FIs need to be directed towards archetypes and EPUs according to all building characteristics to yield scalable benefits. If FIs are not properly distributed, the desired targets are not achieved and the FIs policy becomes meaningless [54].

Impact of occupant behavior on the effectiveness of FIs: A growing body of literature recognizes occupant behavior (OB) as the major reason which creates a gap between actual and simulated energy use of a building [56,57]. OB is a major area of interest within the field of building energy performance. OB includes occupancy period, occupant movement and their interactions with the buildings' systems and appliances [58]. Literature indicates that ignoring the impacts of actual OB can result in an over prediction of savings from the energy upgrades. The difference in energy use can be as high as 80% [59]. The energy differences can exist even for homes with similar vintage sizes and number of occupants [60]. Hence, this inaccurate measurement of energy savings will impact the effectiveness of the FIs. Furthermore, the majority of the utility-based FIs are based on the energy savings reported from simulation results. With the change in building operation, the number of applicable incentives will change [40]. Post-occupancy evaluation studies can provide empirical evidence on the actual performance of GBs [16]. Therefore, more robust energy models based on monitored or realistic occupant behavior will help accurately evaluate the effectiveness of FIs. To date, there are few studies that have used monitored data to generate energy model for low rise residential buildings [61,62]; and consequently, a limited understanding of the impacts of OBs on the effectiveness of available FIs.

Neighborhood energy planning frameworks for allocating FIs: FIs are scarce economic resources that need to be properly allocated to obtain maximum social benefits [63]. Solutions for energy efficiency have largely focused on single buildings, while solutions for building stock are largely overlooked [27]. Despite the significant impacts of building archetypes, neighborhood size, climate and energy sources [64–66]; the relationship between the impact of neighborhood design and energy efficiency is not well understood. Knowledge of neighborhood level energy demand will help to properly allocate FIs and hence obtain a higher level of benefits. Hence, there is a need for a comprehensive framework that can be used to allocate FIs.

Considering the above limitations and gaps in the existing literature, the following research questions arose:

1) How can lifecycle thinking be incorporated into FIs planning for GBs?
2) How can buildings be operated to yield energy, environmental and human health benefits under existing FIs?
3) How can building characteristics, occupancy and preferences affect FIs planning?
4) How can uncertainties and regional variations be integrated with FIs evaluation framework?
5) How can limited public resources be directed for effective allocation of FIs at neighborhood scale?

1.3 Research Motivation

The building sector can be a major player in sustaining and improving the global environmental quality compared to the transport and other industry sectors; hence, a paradigm shift is required from conventional buildings towards GBs. This research is strongly motivated by the urgent need to evaluate FIs policy instruments to increase GBs stock. Under the short time window needed to perform all possible actions for a safer future, limited resources and finances need to be strategically allocated. This is especially important in the Canadian context, where the building sector is a major consumer of energy and is responsible for up to 12% of the country's GHG emissions [67]. In Canada, the building sector's energy use continues to rise, with the residential sector alone showing an 8% increase from 1990 to 2015 [68]. Researchers argue the potential of the building sector of Canada to address climate change is underestimated and needs to be prioritized, especially for deep energy retrofits in the next decade. Hence, new building energy codes and complimentary FIs are being deployed, e.g. BC Energy Step Code and the tiered rebates for different levels [69]. In order to reach GHG reduction targets, GBs stakeholders must be provided with a proper planning framework and checklists to support FIs planning and decision making.

This thesis contributes to the on-going debate on identifying pathways to achieve GBs through FIs while focusing on topics of life cycle costs, energy monitoring and modelling, environmental impacts, indoor emissions and human health. A robust decision support framework is proposed that evaluates the effectiveness and efficiency of FIs considering OB, operation, building archetypes and regional variations at individual building and neighborhood levels is developed and tested through case studies. The case studies include new residential and a public building with field and simulated data located in British Columbia, Canada. The framework will help in assessing the effectiveness of existing FIs and point out the inconsistencies that need to be considered for their improvement. The research will be beneficial to policy makers, end-users, developers and building managers. The research makes a valuable contribution to the existing literature by use of monitored data, calibrated energy models and a detailed sensitivity analysis that combines the application of existing life cycle thinking approaches with FIs to attain realistic solutions and provides direction for FIs planning strategy improvements.

1.4 Research Objectives

The main objective of this research is to develop a decision support framework for a life cycle thinking-based evaluation of financial incentives for green buildings in Canada. The specific sub-objectives of this study are as follows:

1) Investigate and rank energy conservation measures of new residential buildings based on occupancy, environmental and economic parameters
2) Evaluate and compare the cost and environmental effectiveness of financial incentives for residential buildings under uncertainty
3) Determine the efficiency of financial incentives for residential buildings and neighborhoods

4) Prioritize and rank public building operation using life cycle thinking approaches based on human health and environmental impacts

1.5 Meta Language

This thesis has used ubiquitous scientific terms that are widely understood and accepted. Some technical terms, however, may carry a broader meaning and have been defined in **Table 1-1** to ensure a consistent understanding of the current work throughout the thesis.

Table 1- 1 Meta-Language of key terms

Keywords	Description
Effectiveness	The degree to which objectives are achieved and the extent to which targeted problems are solved. E.g. energy target for BC building energy code.
Efficiency	To reach an intended target by using the fewest possible resources. E.g. "X" % cut in energy use of the house by the provision of "Y" $ of rebates with least negative environmental impacts compared to alternatives.
Financial incentives (FIs)	Financial Incentives are external monetary incentives for energy efficiency in green buildings unless stated otherwise. Examples: rebates, loans etc.
Life cycle thinking (LCT)	Life cycle thinking is used to incorporate economic, environmental and/or social impacts of a product, process, or a system throughout its life cycle, from raw material extraction to the eventual end-of-life. These approaches were used to evaluate impacts of energy upgrades and building operation strategies on economics and/or environment.
Decision support system (DSS)	Represents a system of model, tool and/or framework to aid decision making. It may comprise models, modules, sub-models, calculation tools and frameworks and is executable.
Framework	Refers to holistic methods used to achieve the overall goal of the research (E.g. decision support framework for evaluating financial incentives policy).
Methodology	Terms methodology, methods and techniques are used interchangeably to define the applied procedure.

1.6 Thesis Structure and Organization

This thesis consists of eight chapters that focus on the evaluation of financial incentives for green buildings. **Figure 1-1** shows the interconnections between the research objectives and thesis chapters.

A description of these chapters is given below:

Chapter 1 provides a broad view of the research area and identifies research gaps. It also provides the motivation behind research and the objectives and deliverables, research concepts and the overall financial incentives evaluation framework proposed in the study.

Chapter 2 provides an insight into the key research phases and the methods followed in achieving the goal of each phase. Each phase of this methodology is further detailed in the content chapters 4 to 7.

Chapter 3 provides a comprehensive literature review on the state-of-the-art financial incentives, effectiveness evaluation in context green buildings and current limitations in the existing literature. The gaps identified in this chapter were used to develop the research objectives and methodologies. The literature-based database developed in this section was used in the content chapters 4 to 7.

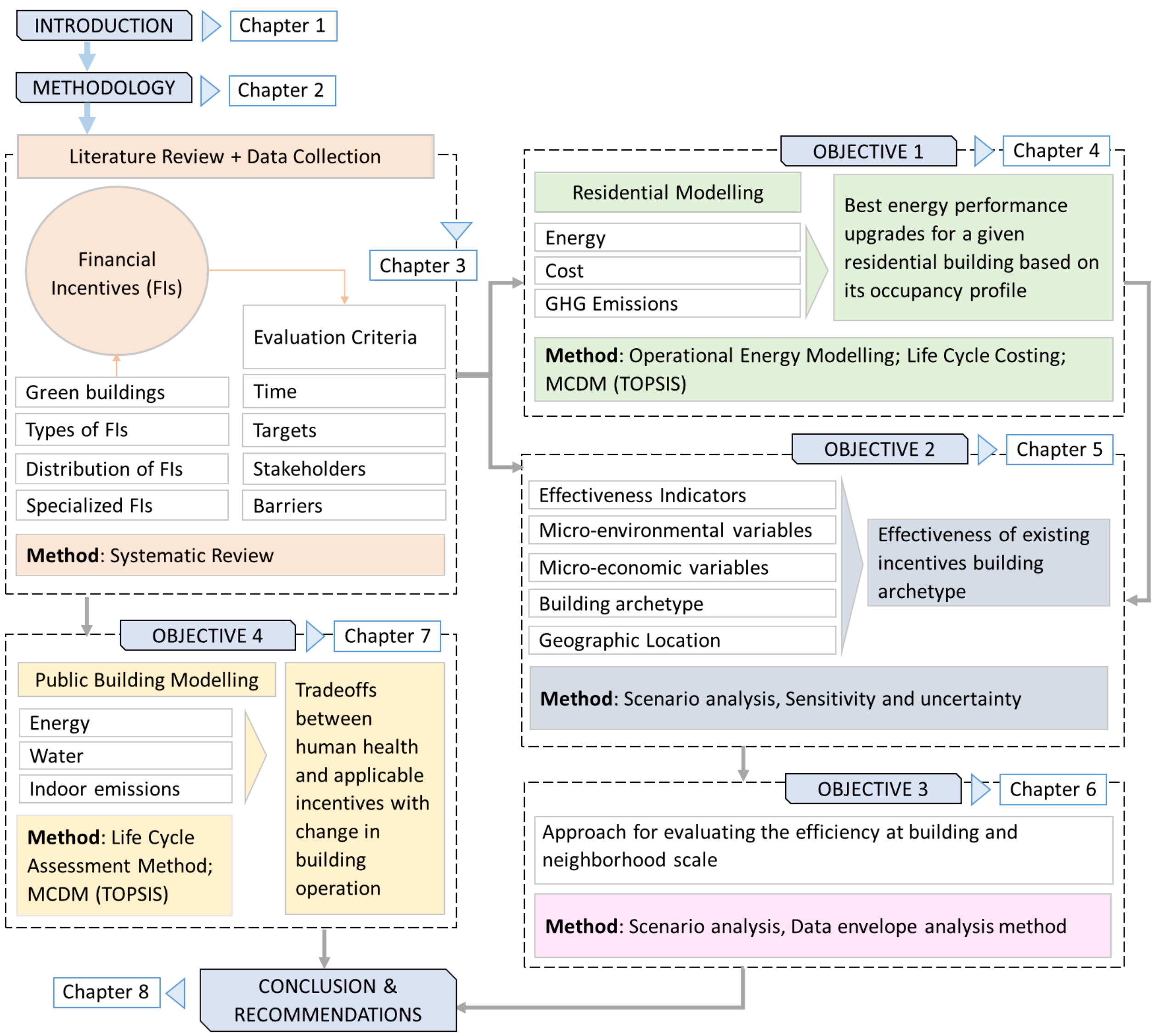
Chapter 4 presents the operational energy and life cycle cost analysis of energy upgrades provided under different occupancy profiles. This chapter makes use of field energy data and uses calibrated energy models to assess the life cycle economic and GHG reduction potential of residential buildings under different occupancy profiles.

Chapter 5 provides the core methodology of the location-based impact effectiveness index, which aligns with the expectations of the 2nd objective. A new index is introduced that can help in assessing the cost and environmental effectiveness of the FIs. The effectiveness index is determined with respect to individual buildings. Sensitivity analysis is also incorporated considering findings from Chapter 3.

Chapter 6 evaluates the efficiency at building and neighborhoods scale under existing incentives structures. The data envelopment analysis method was used to evaluate efficiency from both investors and government perspectives.

Chapter 7 provides the effects of change in public building operation on human health, ecosystems and resources. Field data related to indoor emissions and life cycle assessment method are used to rank operation strategy and determine ranking implication on existing incentive eligibility criteria. The chapter also fulfills the last objective of the study.

Chapter 8 provides the main findings, recommendations, originality and future research potential.

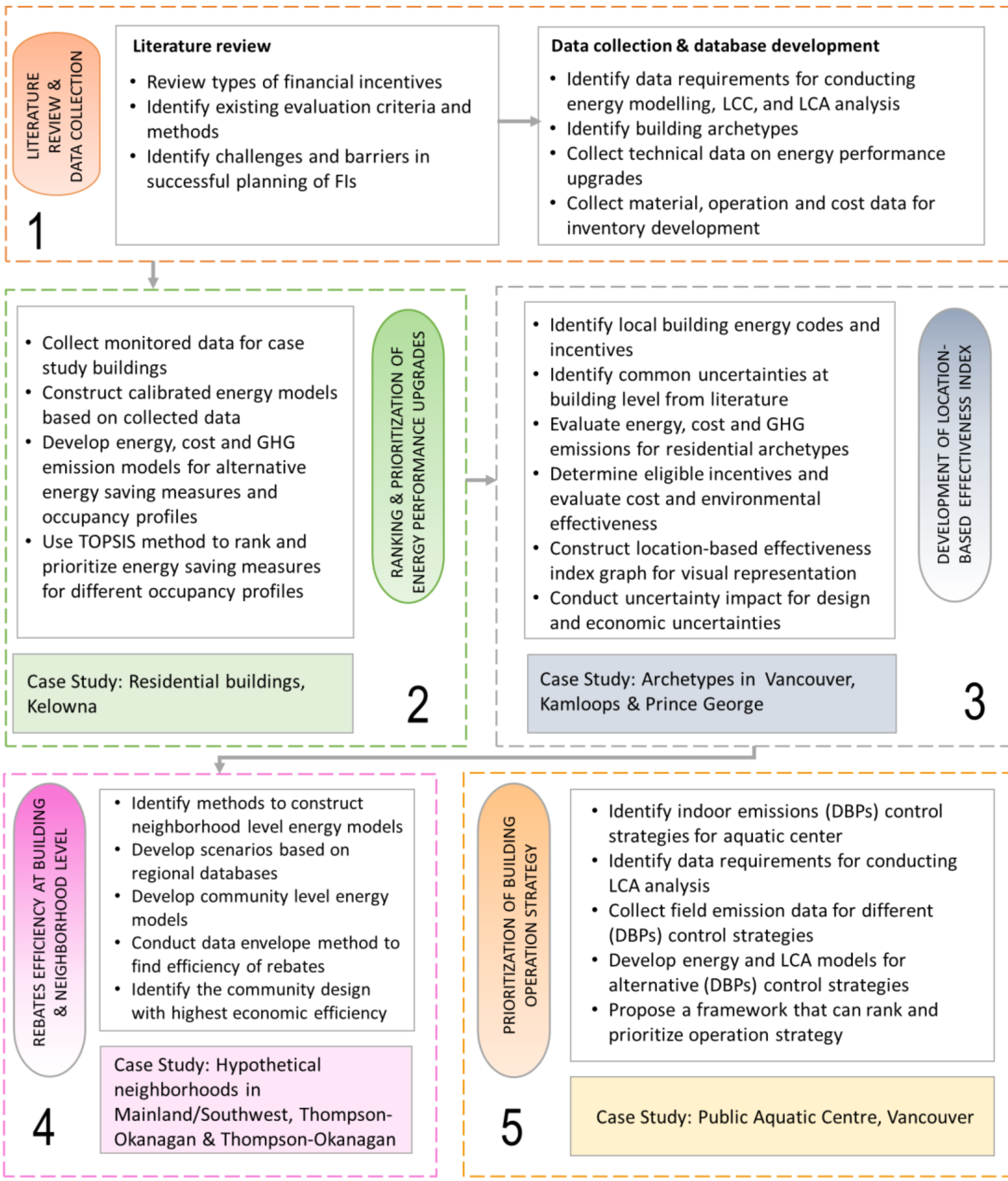


Note-TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution; MCDM: Multiple-criteria decision analysis; FIs: Financial incentives; GHG: greenhouse gas.

Figure 1-1 Thesis Organization

Chapter 2 Research Methodology

The focus of the research is to develop a planning framework for financial incentives to enhance the construction of green buildings (GBs). The objectives provided in section 1.4 were achieved through 5 research phases. The details of the proposed framework and the demonstration steps are explained in the body of this thesis. **Figure 2-1** depicts the connection between the research phases.



Note-TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution; FIs: Financial incentives; GHG: greenhouse gas; LCC: Lifecycle costing; LCA: Life cycle assessment; DBPs: Disinfection byproducts

Figure 2-1 Integration of Objectives, Information Flow and Thesis Organization

Phase 1-Literature review and data collection

This phase involved a comprehensive review of literature related to FIs available for GBs in Canada, FIs evaluation criteria and methodology and challenges pertaining to the success of FIs. The systematic review was performed using the document analysis technique. High impact journal articles were given priority for review. In addition, literature was collected from peer-reviewed articles, technical reports, conference publications, books and graduate theses. Data on FIs to make Canadian residential and commercial buildings more energy efficient was collected from municipal, utilities, provincial and Natural Resources Canada (NRCan) databases. Data related to energy performance upgrades, building archetypes, utility costs and building energy codes were collected from local developers and construction practitioners. 'RS Means' data was extensively used for cost data in addition to values obtained from construction experts. The detailed findings of the literature review are provided in **Chapter 3**.

Phase 2-Ranking and prioritization of energy performance upgrades based on occupancy profile

This phase proposed a methodology for ranking and prioritization of energy performance upgrades for newly constructed residential buildings based on occupancy profiles. Here two identical residential buildings with different occupancies were tested utilizing calibrated energy models, life cycle cost models and operation related GHG emissions. On-site data was collected from the intrusive-load monitoring technique and used to calibrate energy models on HOT2000 using Federal Energy Management Program (FEMP) and ASHRAE 14 benchmarks. In order to represent occupants' preference that can range from pro-environmental to pro-economic, different weights were assigned to the environmental parameter (i.e., GHG emissions reduction) and economic parameters resulting in five preference scenarios. TOPSIS method was utilized to rank and prioritize energy performance upgrades for different occupancy profiles and preferences. This methodology is detailed in **Chapter 4**, section 4.2.

Phase 3-Location-based effectiveness evaluation methodology

A multi-stage methodology was proposed in Phase 4 that utilizes a rule-based screening method to identify the most appropriate energy performance upgrades; evaluate the cost and environmental effectiveness of applicable FIs for residential archetypes; and check the sensitivity of FIs impacts against key design and economic parameters. The methodology was demonstrated through a case study of rebates offered with a new building energy code applied to seven residential archetypes. Environment, technical and cost data related to energy performance upgrade collected in Phase 1 were used to develop energy models on Building Energy Optimization Tool (BEopt) while the lifecycle cost analysis was conducted on MS-excel. Local sensitivity analysis was conducted to determine the impact of uncertain design and economic parameters on the effectiveness of FIs. Detailed methodology is present in **Chapter 5**, section 5.2

Phase 4-Rebates efficiency at building and neighborhood level

Energy, cost and GHG emission results evaluated in Phase 4 for different building archetypes were used to determine the economic efficiency of rebates at building and neighborhood levels. The bottom-up energy modelling technique was utilized to evaluate energy, cost and GHG emissions at the neighborhood level. To determine the economic efficiency, the data envelope analysis (DEA) method was used. Hypothetical residential building neighborhoods in three locations were constructed based on NRCan Statistics reports. The efficiency of FIs was determined using the DEA-Solver tool to identify the building stock with the highest benefits and identify the direction where maximum FIs should be allocated. A more detailed methodology for this phase is provided in **Chapter 6**, section 6.2.

Phase 5-Prioritization of building operation strategy for environmental and health benefits

Incentives for commercial and public buildings are assigned based on savings in operational energy intensity. For a holistic assessment of incentives, it is essential that the impacts of building operational energy are evaluated for overall environmental and health impacts. In this phase, a methodology was proposed for prioritizing building operation strategy that provides the highest health, environmental and resource benefits. The methodology was developed for a public aquatic center building in Vancouver, BC. Indoor emissions collected from field study, operational use of water, energy and chemical resources were integrated to determine operation strategy with the highest benefits. Detailed energy modelling and LCA were conducted to prioritize the most suitable building operation strategy using the TOPSIS method. Ultimately the eligibility criteria of incentives were compared with the impacts of operational strategy. The detailed methodology for prioritization of public building operation strategy is provided in **Chapter 7**, section 7.2.

Chapter 3 Literature Review

Parts of this chapter has been published in the Elsevier journal *Renewable and Sustainable Energy Reviews and Renewable Energy*, as articles titled “Evaluation of financial incentives for green buildings in Canadian landscape” and as conference proceedings in *CSCE General Conference 2017* as “Financial incentives for green residential buildings in Canada: A review from a regulatory lens” [21,70].

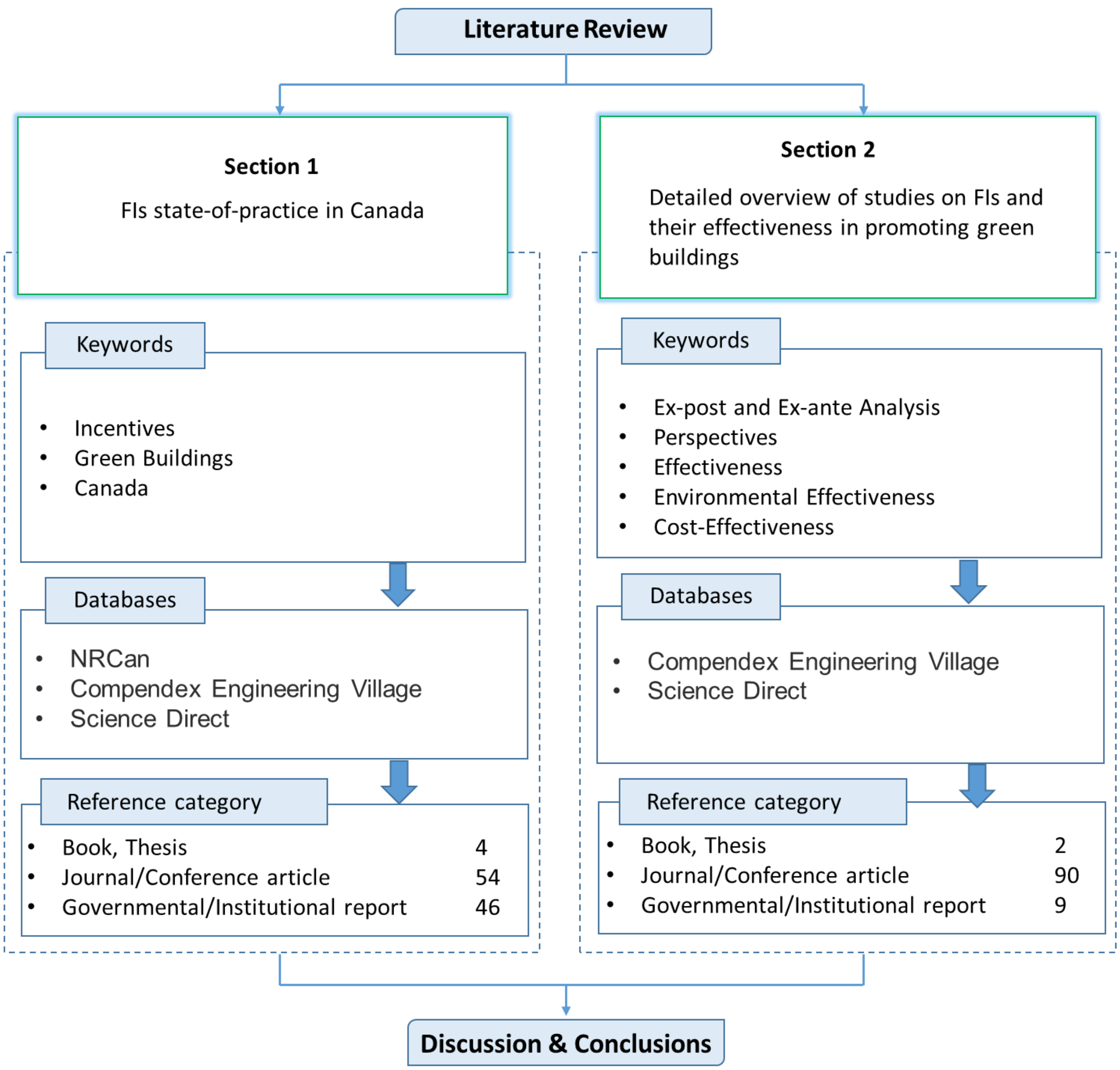
3.1 Background

Climate change like COVID-19 pandemic is a global emergency; however, its negative outcomes are slower in materializing and have much graver impacts in the long run [71]. Greenhouse gases (GHG) from anthropogenic activities are a major driver for climate change. According to the International Energy Agency (IEA), the building sector is a major contributor to the global GHG and accounts for more than one-third of annual emissions [72]. Making buildings more energy efficient can help to address climate change. Financial incentives (FIs) are important and widely implemented policy instruments that can help to reduce buildings' energy and GHG emissions [18,19]. FIs[1]for making green buildings (GBs) can be in the form of grants, loans, rebates, and tax credits [18,25,73,74]. FIs assist in increasing the energy efficiency of buildings by removing financial barriers, penetration of innovative low-carbon technologies and/or helping the implementation of other policy instruments [75–78]. They are important in setting a stage for the implementation of more stringent bylaws and policies promoting higher building performance standards (e.g. net-zero energy buildings). Due to COVID-19, the impacts of existing FIs for buildings will become even more important as energy retrofitting and integration of clean carbon technologies in buildings are seen as an ideal response to simultaneously pursue climate change mitigation and revival of an economy damaged due to the pandemic [79]. Therefore, successfully utilizing FIs in promoting GB is crucial to ensure minimum wastage of national resources with maximized outcomes.

[1] The term “Financial Incentives” or “FIs” throughout the paper will refer to Financial Incentives for energy efficiency in green buildings unless stated otherwise

Knowledge on a country's state-of-the-art FIs is needed to lay a solid foundation for further improvements in the effectiveness of its energy policy. Reviews on FIs are available for a number of countries. However, these reviews either focus on a single FI in a number of countries like the work by Shazmin et al. [17] on property tax incentives for a number of countries including Canada, or they focus on policy instruments in countries other than Canada; example, Sebi et al. [80] work on incentives in Germany, France, and the US or Bertoldi et al. [81] work on financial instruments for residential buildings in Europe. Some recent reviews focus on policy instruments in a single country, such as G. Liu et al. [82] work on policy instruments (including FIs) in China. Alternatively, they look at FIs present for a particular energy upgrade, such as Curtin et al. [83] study on FIs present for low-carbon technologies (solar systems, heat pumps etc.). The existing literature predominantly focuses on policy instruments in the US, Germany, or China, and not specifically on the state of FIs in Canada. The limited studies that do consider Canada either focus on a particular building type, such as a study by Hoicka et al. [84] (residential building retrofits); focus on a particular program, such as work of Nadel and McMahon [85] on lighting energy, or are too old to extract meaningful results, such as Stern et al. [86] (performed in 1986). Overall, the published body of knowledge either focuses on specific FIs (e.g., tax incentive); specific buildings (e.g., residential); specific energy measure (e.g. heat pumps) or a specific stakeholder (e.g., the private-home owners); and a holistic examination of available FIs for buildings in Canada is still missing in the literature. Therefore, with a particular focus on Canada, this chapter attempts to take a closer look at the state-of-the-art green building financial incentives to lay a ground for designing future incentives while improving the existing incentive strategies. This chapter provides a comprehensive review of the state-of-practice of energy related FIs available for residential and commercial buildings in Canada and effectiveness evaluation of FIs in GBs. In order to achieve these objectives, a systematic review using the document analysis technique has been employed [87].

The methodology for this chapter involved the use of specific keywords, specialized databases, and document types that ranged from journal articles to books. A keyword search was conducted in two main bibliographic databases: Compendex Engineering Village and Web of Science. The literature published after 2010 was given a priority, so as to provide a more up-to-date status of the GB related FIs literature. Document analysis technique method used for this research involved the review of all forms of technical writings; for example, peer-reviewed articles, technical reports, conference publications, books and theses, that can help in evaluation. The number of peer-reviewed journals, conference proceedings, books, and other literature sources relevant to the field of GBs considered are shown in **Figure 3-1**. In addition to these, various municipal, utilities, provincial and Natural Resources Canada (NRCan) databases were explored for determining the FIs available for residential and commercial buildings in Canada. This review provides an assessment of FIs in Canada implemented until 2018 unless new incentives come to the practice.



Note- FIs: Financial incentives; NRCan: Natural Resources Canada

Figure 3-1 Research methodology

The literature is collected from articles of journals with high impact factors. The impact factor represents how frequently the scientific community is citing the journal [88] and this parameter is considered when comparing and ranking journals [89]. Journal articles with impact factors greater than 2.5 were prioritized in this chapter. **Table 3-1** shows the journals that were cited more than twice in this review study along with their impact factors. In the research presented, the terms FIs, financial instruments, and the economic instrument are used interchangeably and represent the same meaning.

Table 3-1 Major journals used in the review

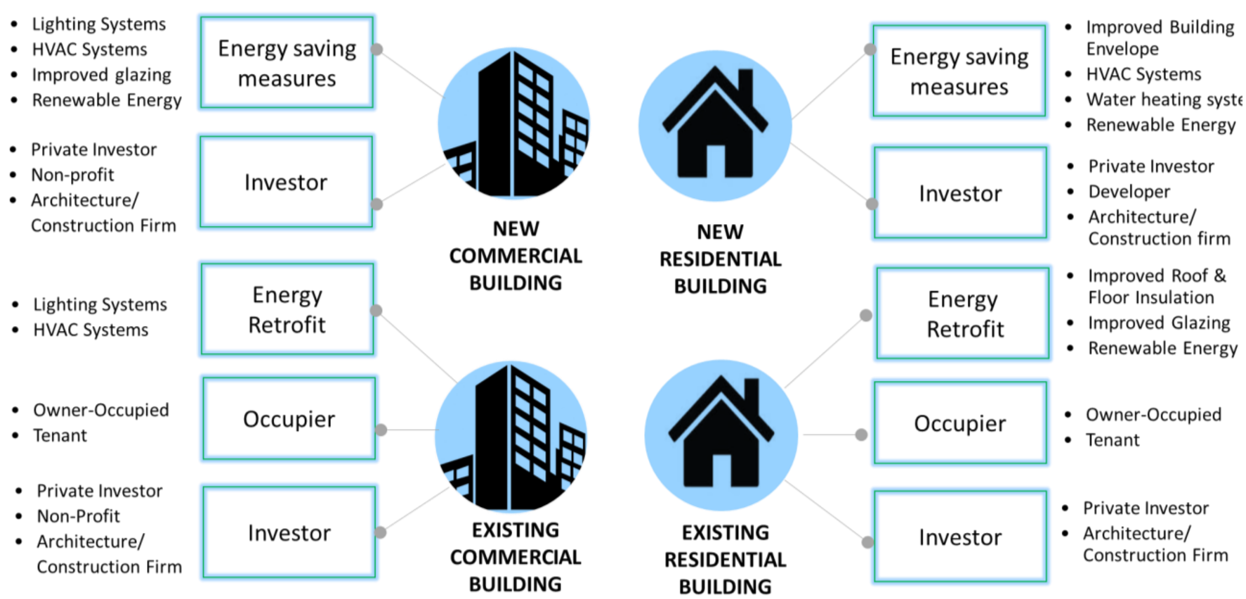
Journal	5-year impact factor
Renewable and Sustainable Energy Reviews	12.348
Journal of Cleaner Production	7.491
Energy	6.046
Energy Policy	5.693
Energy Economics	5.790
Energy and Buildings	5.055
Technological Forecasting and Social Change	5.179
Building Research & Information	3.744
The Energy Journal	2.739

The relevant literature was screened by reviewing the titles, summaries of reports, abstracts of articles, keywords, conclusions and key findings. In order to synthesized the information a database of reviewed information was constructed in excel spreadsheets. This enabled comparison of findings and analyzing how financial incentives are being addressed in literature. Through this database it was possible to identify research trends and missing knowledge gaps.

3.2 Canada's Building Energy Efficiency Landscape

The Paris agreement and the Pan-Canadian Framework have encouraged the federal and provincial governments in Canada to set carbon mitigation targets for the year 2030, which will ensure that the global temperature remains below the limit of 1.5^0C of the pre-industrialized levels. This demanding goal can be achieved through the application of effective energy efficiency measures in all sectors. Canada's building sector is a major consumer of energy and is responsible for up to 12% of its GHG emissions [90]. The majority of the energy consumed in the residential sector is used for space heating (64%) and water heating (19%), followed by electrical appliances, lighting and space cooling that use the remaining portion of energy [91]. The commercial sector accounts for 11% of the total energy consumption, with the majority accounted for space heating (56%), followed by auxiliary equipment (14%)[91]. Furthermore, more than 80% of the existing buildings were constructed before 1996 and did not conform to the more stringent energy efficiency codes for new buildings [90,92,93].

Low energy GBs can be achieved by three types of energy interventions: energy conservation, energy efficiency and energy saving measures [94]. New buildings can be designed to be green by developing better building thermal envelopes, using energy efficient equipment and appliances and using renewable energy technologies [95]. Existing buildings can be improved through retrofitting, which includes improvements in the thermal envelope, use of energy efficient equipment and appliances, use of renewable energy technologies and changes in human behavior [96,97]. In addition, ownership structures of residential and commercial buildings vary significantly, leading to different stakeholders' involvement responsible for energy efficiency improvement (**Figure 3-2**).

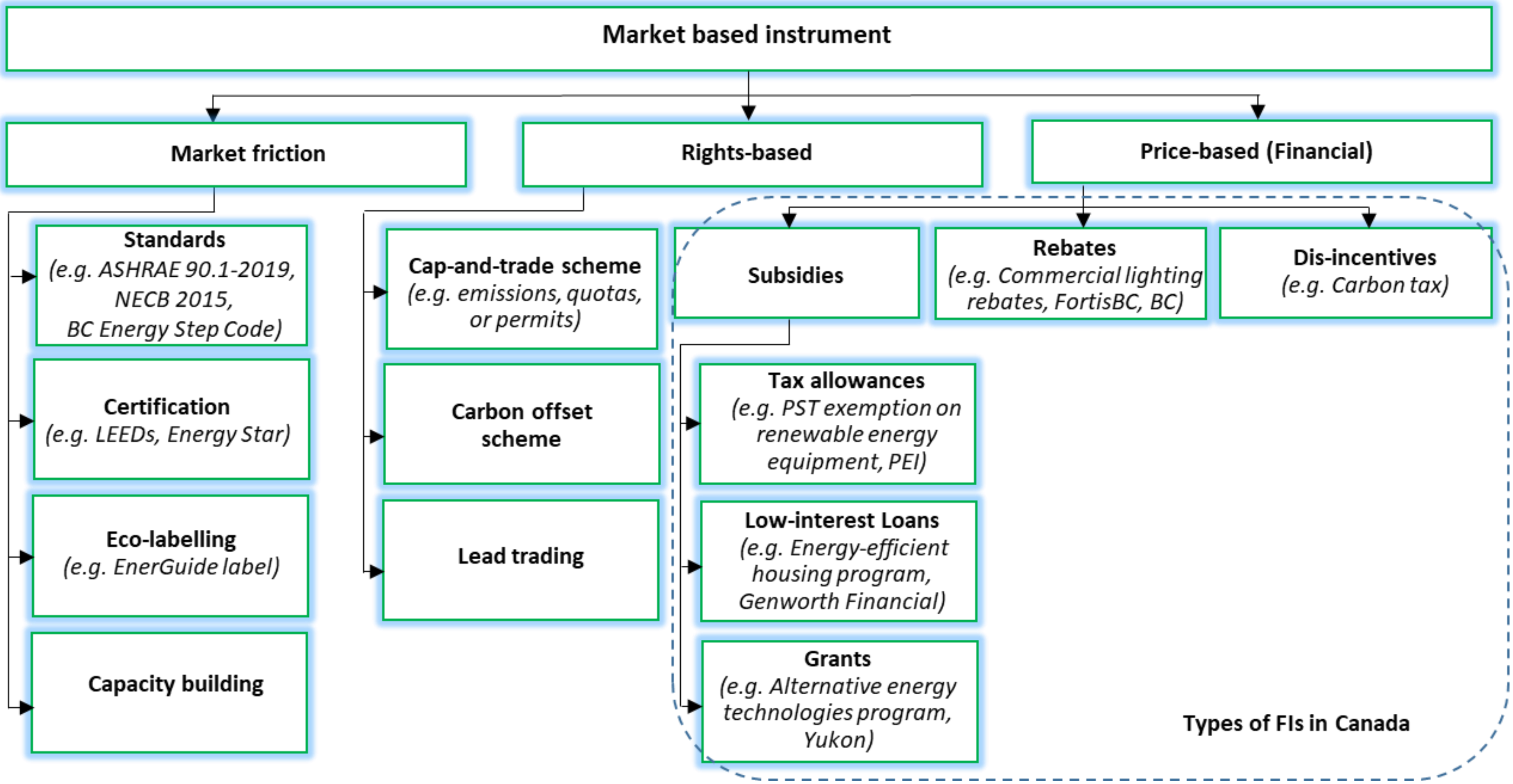


Note- HVAC: Heating, ventilation, and air conditioning

Figure 3-2 Energy improvements and investors for residential and commercial buildings

3.3 Financial Incentives for Green Buildings

A multitude of different policy tools are available that can help in the market penetration of GBs and achieving energy reduction targets. Policy tools can be divided into two groups: (1) Regularity or Command and Control (CAC); and (2) Market Based Instruments (MBI) [98–100]. CAC provides legislation defining the legal limits; for example, energy efficiency regulations [100].



Note- ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers; NECB: National Energy Code of Canada for Buildings; LEEDs: Leadership in Energy and Environmental Design; PST: Provincial Sales Tax; PEI: Prince Edward Island.

Figure 3-3 Typology of market-based instruments for green buildings in Canada

MBIs are considered more powerful than CAC as they offer some form of incentive to the user [98]. MBIs can be sub-divided into three categories: market friction reduction, rights-based and price-based [101]. **Table 3-2** describes these instruments, while **Figure 3-3** provides examples of MBI available for the promotion of GBs in Canada.

Table 3-2 Categories of market-based instruments (*Source*: [100,102–105])

Category	Description	Instrument examples
Market friction-based	Market friction-based instruments help in achieving policy targets by improving the conditions of existing private markets. These market-based instruments are non-financial	-Eco-labelling -LEED (Leadership in Energy and Environmental Design) Standards -Energy Star ratings of appliances
Rights-based	Rights-based or quantity-based instruments specify the amount of emission permitted under a specified condition	-Cap-and-trade scheme for provinces (emissions, quotas, or permits) -Carbon offset scheme -Lead trading
Price-based	Price-based instruments provide changes in prices in existing market conditions	-Subsidies on high efficiency appliances -Carbon tax on fossil fuel used

FIs are the types of price-based MBIs that are provided extensively by government and utility providers. A brief description of different types of FIs is provided in **Table 3-3**. It should be noted that among the policy instruments described in this section, no single policy instrument can be considered as a silver bullet for achieving a country's carbon mitigation goals and the effectiveness of an instrument changes with respect to context.

3.3.1 Subsidies

Price-based or financial instruments can be in the form of subsidies, rebates and dis-incentives. The subsidies can be provided in the form of loans, tax-allowances or grants [106].

Loan incentives: Loans are a common type of FI offered by governmental organizations and commercial banks [83,107]. Loans for GBs typically charge a lower interest rate over a longer duration compared to other commercial loan types [107]. The amount of loans offered vary from time to time and depend on macroeconomic conditions [108]. A list of GB loan incentives present in Canada is provided in Appendix A, Table A1. In Canada, loan incentives for GBs are offered by a number of institutions: Canada Mortgage and Housing Corporation (CMHC) [109], banks [110], utility companies and municipalities [111]. The majority of the loans are offered for a five-year period. Loans are available for the construction of new homes [112], retrofitting of commercial buildings [113] and upgrade of individual systems; such as Residential Earth Power Loan - for Cold Climate Air Source Heat Pumps, Manitoba (MB) [114]. Compared to other provinces, MB offers the largest number of loans for GBs.

Table 3-3 Financial Incentives for green buildings

Types	Description	Ref.
Financial Incentives	FIs are the monetary support provided by the government or utility providers. Financial Incentives offered in the forms of subsidies, rebates, or disincentives require certain energy efficiency-related conditions to be fulfilled by the investors.	[17,18]
Subsidies	Subsidies are offered on energy upgrades/retrofits that enable investors to perform energy upgrades at a lower rate than the market price. The subsidies can be in the form of grants, loans or taxes.	[106]
Loans	Loan incentives are used to enable the installation of an energy retrofit or energy efficient equipment at a low-interest rate. Low interest enables the viability of a larger number of retrofits compared to the higher interest rate.	[115,116]
Grants	Grants are monetary incentives that do not require to be paid back and are popular due to their simplicity. Grants account for a large sum of money and are usually offered by the government at the federal level.	[83,117]
Tax incentives	A tax incentive can be defined as monetary credit, deduction or exemption on the tax required to be paid if the energy target/energy upgrade was not performed for the building.	[118]
Rebates	Rebate is the full or partial amount returned on the applied energy upgrade measure. The rebates are usually offered by utility providers on the purchase of energy efficient equipment.	[119]
Disincentives	Dis-incentives are financial instruments that work as negative reinforcement towards energy efficiency improvements. A carbon tax is one of the most common dis-incentive and has been found to be successful in mitigating carbon emission.	[120]

Tax incentives: Tax incentives are one of the most popular GB incentive offered by governments [121,122]. Tax incentives can be used either in the form of positive incentives that encourage GBs construction such as tax rebates, reductions, exemptions (or tax breaks), preferential tax rate, tax deferral and tax reimbursement [123], or as disincentives to discourage unsustainable practices [110]. Compared to other energy efficiency-related policy instruments such as increments in interest rates or energy prices, taxes provide swifter changes in energy use [123]. The bases of these incentives can also be used to include accelerated property tax assessments, rate of property tax assessment and certification levels for GB [17]. Tax exemption incentives or tax breaks are provided to developers for a limited time period and scope. Compared to other countries, Canada's incentives are based on the exemption model rather than rebates and/or reductions [17]. In Canada, there are limited number of tax incentives for GBs (see Table A2). British Columbia (BC) has 100% property tax exemption for eligible devices as well as energy upgrades that result in Gold or Platinum level Leadership in Energy and Environmental Design (LEED) certified buildings [124,125]. In Quebec (QC), RénoVert Tax Credit is provided for the energy renovation of residential buildings [126]. Among various FIs, tax incentives have been most effective from an environmental and economic point of view [127]. Hence, there is a need to increase the number of tax incentives available for GBs in Canada.

Grant incentives: Grants are another way to offset green residential building costs [128]. They are used as an incentive for the adoption of GBs at an individual and community level [83]. Grants are applied to a certain percentage of per capita costs or investment costs of a component. Since a specific economic benefit is associated with GB financial grants, they have proven to be quite successful. Due to a large amount of capital needed for grant incentives, they are mostly suitable for regulatory incentives at the provincial or national level [129]. In contrast to the financial tax incentives offered for green construction, numerous grants are available at both provincial and municipality levels in Canada. A list of GB grants present in Canada is provided in Table A3. It is observed that similar to loan incentives; grants are offered for new construction, energy renovation and specific systems upgrading. The majority of the grants are provided through utility companies in different provinces. The largest number of grants are available in QC through utility provider "Énergir" [130]. Some special grants, such as Home Energy Low-Income (HELP) [131] are specifically designed for building users with low income [130].

3.3.2 Rebates

Rebates are financial gains received by building owners or developers [18], usually when the energy improvement is implemented in the building. Globally, the deployment of rebates has been successful in achieving high energy savings [132]. Rebates offered by utility programs exceed loan and grant incentives for buildings. Energy saving potential through upgrades is high for commercial buildings, but this is accompanied by higher initial investment requirements. To counter these costs, rebate amounts up to CA$ 500,000 are provided by the government of Nova

Scotia (NS), while most other provinces are offering much less (up to CA$ 50,000). In the residential sector, rebates offered by municipalities are common for Alberta (AB), while utilities offered rebates are more common in BC, QC, Ontario (ON) and Newfoundland and Labrador. Provincial rebates are offered for residents of NS, Prince Edward Island (PEI) and Yukon. Overall, AB and BC provinces are highly committed to developing green residential and commercial buildings through rebates with the aim of creating a sustainable future for their residents.

3.3.3 Dis-incentives

Dis-incentives are financial instruments that work as negative reinforcement towards energy efficiency improvements [120]. The tax follows the rationale that the polluter pays for the negative impacts of his energy use in the form of a penalty if the emission rate exceeds a specific limit [133,134]. Carbon taxes have been employed in few other countries, including the Netherlands, Sweden, Norway and others [135]. These are determined to be cost-effective instruments that utilize minimum resources [136]. BC has a carbon tax on the use of natural fossil fuels in order to discourage the use of these resources. Carbon tax in BC is applied based on the taxable fuel consumption of a household that relates to cooking, heating and transportation. The prices are applicable to gasoline, diesel, propane, coal and natural gas [137]. Carbon-tax introduced in BC has been deemed successful in reducing GHG emissions by 19% with no economic losses [138]. Similarly, a recent study determined the impact of BC’s carbon tax in reducing natural gas use by 7% in the residential sector [139]. AB and QC have similar carbon pricing systems. Recently, a nationwide tax system has been introduced in Canada, which is applicable to provinces where the carbon pricing and/or carbon tax systems are still absent under the “Greenhouse Gas Pollution Pricing Act”[140]. The federal government's proposed carbon tax is currently offered at CA$45/ton and will be increased at the rate of CA$10/ton per year until the year 2022 [141].

3.3.4 Targeted incentives

Targeted incentives are needed to address the energy improvement needs of specific stakeholders and/or buildings that are vulnerable to high costs risks [142,143]. Targeted incentives provided on sub-sets populations can yield a higher degree of desired outcomes [84]. **Table 3-4** shows the distribution of some important targeted incentives in different provinces of Canada.

Table 3-4 Summary of Targeted Financial Incentives in Canada

Province	Residential					Commercial				
	Low-income	Heritage buildings	Non-profit	Aboriginals	Landlord and tenants	Low-income	Heritage buildings	Non-profit	Aboriginals	Landlord and tenants
Alberta	✓		✓			✓		✓		
British Columbia	✓		✓	✓		✓		✓	✓	
Manitoba	✓	✓		✓	✓				✓	
New Brunswick	✓		✓							
Newfoundland and Labrador	✓									
Nova Scotia								✓		
Nunavut										
Ontario	✓	✓		✓				✓		
Prince Edward Island	✓									
Quebec	✓				✓	✓		✓		
Saskatchewan										
Yukon										

Low-income population: Lack of affordable housing is a recognized problem in major cities of Canada. The low-income population is especially vulnerable and needs financial aid to improve their houses' energy performance and reduce the energy bills. Studies have shown the willingness to participate in an energy efficiency program is especially minimal for low-income families dwelling in older residences [144]. These incentives are being offered by both utilities and provincial governments [131,145–152]. Some of the incentive programs cover the total costs of specific energy improvements [131,151,152], while others offer increased incentives such as those offered by Énergir and Gazifère utilities in QC [149,150]. In QC, the rebates for low-income residents are double the amount of those offered for a normal housing energy upgrade. Manitoba Hydro offers free small scale energy upgrades for such buildings [153].

This implies low-income incentives are present in most provinces, but the amount and type of incentive being offered vary. Recent studies on COVID-19 indicate an expected increase in energy poverty as the impacts of lockdown and related economic losses become more evident [154,155]. Hence, more specialized incentives for the low-income population will be required to face the current pandemic' economic impacts.

Buildings built during a specific time period: The majority of Canadian buildings were constructed prior to the implementation of new energy efficient building codes. Furthermore, old buildings that form a part of the cultural heritage have limited energy upgrades options and require special incentives for energy improvement [143,156]. Hence it is essential to reduce the energy use in these old buildings to meet carbon targets. The Home Weatherization program in Ontario (ON) [157] (for buildings constructed before 1975) and the Power Smart Home Insulation Program in MB [153] (for buildings built before 1999) are good examples of FIs targeting buildings built under older building codes. Though a number of rebates and subsidies are available for retrofitting existing buildings, only ON and MB provinces seem to target buildings belonging to a specific time period. Such incentives are required to ensure that buildings retrofits that will yield maximum benefits are prioritized.

*Non-profit organizations**:*** Non-profit organizations (NPOs) can help increase energy efficiency by providing awareness and help to marginalized communities. The buildings directly under NPOs usually have high operational costs and FIs can reduce the above costs. Energy efficiency requirements dep end upon the particular services being performed by the NPO [158]. The type of buildings that can benefit from these FIs are sports and recreation, community centers, health centers, religious, social housing, co-op housing, housing for aboriginals etc. These incentives are usually bundled under the same program with incentives for aboriginal housing [151], low-income housing [149], or residential and commercial buildings [148].

Aboriginal population: The future sustainability of Canada's aboriginal communities faces economic, social and environmental challenges [159]. For this reason, specialized incentives have been provided by different provinces to meet sustainability goals. Over time, ON has updated its incentives programmes the aboriginal communities, starting from tax exemptions and moving towards differentiated Feed-in Tariffs and specialized contract and tendering schemes with local ownership criteria [160]. In addition, free upgrades are also offered to aboriginal communities in ON under the First Nations Conservation Program [161]. Manitoba Hydro offers "Pay As You Save (PAYS) Financing" to the aboriginal population to improve energy efficiency through the installation of geothermal systems [162]. Similarly, BC is offering incentives for residential and commercial buildings belonging to aboriginal communities [163]. Aboriginal people are one of the most marginalized communities in Canada with limited energy resources. Only BC, ON and

MB are currently offering incentives for aboriginals. Similar to the scenario with low-income populations, more incentives are required to be deployed for aboriginals at provincial and municipal levels as the current COVID-19 pandemic unevenly impacts Canada's vulnerable populations.

Landlords and tenants: Extensive research has shown that the investment cost for energy upgrades and limited return on investment are major barriers to energy efficiency improvement of the rental housing sector [164–166]. In rental buildings, benefits and costs associated with energy efficient upgrades are not equally shared by the owners and the tenants. In most cases, the benefits of lower energy bills and comfort are reaped by the tenants while the owners have to make capital investments for the energy efficiency improvements [167–170]. This principal agent problem results in a low willingness to invest in energy upgrades even when FIs are available. This is illustrated by Phillips' [171] study that showed that the uptake of grants for insulation was much higher for owner-occupied buildings compared to rented buildings. Therefore, special incentives are needed to ensure both landlords and tenants obtain the benefits. In order to improve the energy efficiency of the rental housing sector, utility providers in two provinces, MB and QC, offer incentives specifically designed for landlords and tenants. Hence, only a limited FIs are available specifically for landlord and tenants in Canada. In addition, studies indicate rental occupancy is increasing in major cities such as Toronto (ON) and Vancouver (BC) where more than 40% of citys' GHG emissions are related to high-rise apartments [172].

Buildings built to specific building standard/code: Provision of green certification to a building adds additional burdens to the costs of GBs [173]. Hence, some FIs in Canada are specifically designed for the rating system and certification of GBs. CMHC and the NS government provides incentives for houses built to Energy Star or R-2000 Standards [109,174]. Similarly, incentives for EnerGuide homes are offered by utility providers in BC and governments of NS and PEI [131,152,174]. The government of PEI also offers incentives for new construction with energy performance either 20% better than Energy Star Homes or 50% better than R-2000 [131]. Some municipalities also offer incentives for energy evaluation before and after energy upgrade of an existing home, such as Edmonton and City of Medicine Hat municipalities in AB evaluation and improved performance [175,176]. In addition, building energy codes are being revised and upgraded in Canada at national and provincial levels, such as the BC energy step code for new buildings [177]. At present, FIs offered in PEI and NS are most adaptable by builders and developers as they are offered over a wider range of energy standards and ratings. Similar efforts are required from other provinces for a faster transition to a more energy efficient building stock.

3.4 Financial Incentives in Canada Regulatory Regimes

Canada's climate and energy policies are interrelated and form a crucial part of FIs deployed for the buildings [178]. Politically, the governance of Canada is distributed into three main levels: (1) federal and (2) provincial and (3) municipal territories. The federal government is mainly responsible for developing national energy policies in line with international agreements and deploying the necessary resources such as provincial-level grants to assist the accomplishment of climate targets. Building standards, as well as assessment criteria, also form a part of the federal government responsibilities [179]. In addition, under the Canadian Environmental Protection Act of 1999, the federal government can place limits on carbon emissions such as through the application of carbon tax on provinces. The provincial governments are responsible for the resources and can follow the standards set by the federal government. There is a wide variety of economic and environmental conditions among different provinces that change the energy demand. Similarly, socio-economic conditions vary and change at urban and rural scales with development [180]; hence, the types of energy upgrades and FIs will vary according to a buildings' location and time of FIs application. Energy decisions performed at provincial levels are used as the basis of FIs offered at the municipality level. Though energy and emission-related decisions are performed at all three government levels, the decisions do not always follow from federal to municipal level [179].

3.4.1 Federal

At the Federal level, most FIs for green residential buildings are in the form of loans offered by financial institutions [130]. The number of incentives offered depends upon the life stage (i.e. design, construction, operation, demolition) of a building and GB certification type. For example, CMHC offers refunds on financial loans up to 15% for an Energy Star rated house and up to 25% for an R-2000 certified building [109]. Different banking organizations in Canada are also offering incentives for homeowners who want to construct or upgrade a house to GB standards. Banks are providing incentives, especially for the installation of solar panels and high energy efficiency equipment [110]. The Canadian Green Building Council also offers registration and certification fee waivers for buildings complying with LEED® Canada under the Homes Affordable Housing Program [181]. The Genworth Financial Canada incentive program for green homes provides a premium refund for energy efficient homes [130]. Overall, several FIs are offered at the Federal level. However, it should be noted that federal incentives cannot be equally availed at all locations in Canada because of differences in demographics, weather, types of constructions, local resources, technologies and components along with certification methods in different regions.

3.4.2 Provincial

Provincial incentives commonly offered through the provincial governments or the utilities are useful in the promotion of GBs. **Table 3-5** provides an overview of FIs available in different provinces of Canada. It is seen that a large portion of FIs are offered by utility companies, mostly in the form of rebates on individual energy upgrades. Compared to other provinces, AB, NS and PEI governments offer the largest FIs. [131,148,174]. AB, however, does not have any FIs from utility providers. In some provinces, organizations play an important part in the energy performance improvement of the building. For example, the Northwest Territories are dependent on incentives provided by Arctic Energy Alliance [182] and do not have FIs from the provincial government, local municipalities and utilities. At the provincial level, BC, MB and SK have a wider variety of FIs.

3.4.3 Municipal

FIs utilized at the municipal level particularly target energy efficiency of housing stocks [183]. Municipal FI models are based on local conditions and are most effective in the generation of GB neighborhoods. Since municipal GB incentives have significant variations regarding end goals, some municipalities are becoming much more efficient with regard to their energy and water use. For instance, the District of Saanich in BC has one of the most elaborate incentive schemes for green residential buildings and offers rebates for houses designed to any four of the energy standards: EnerGuide 80, R-2000, Built Green or Power Smart for New Homes [184]. This increased scope and flexibility have enabled the city to improve its residential buildings. In the same vein, Markham, Calgary and Vancouver are good examples of Canadian cities that have made significant progress in increasing their green building stocks [184]. For commercial buildings in Toronto, two programs, a loan and an Eco-Roof incentive program, specifically target the construction of green and/or cool roofs [113,185]. Programs such as Eco-roof incentive encourage the reduction in energy use and management of storm water of buildings [186]. Therefore, more flexible incentives are needed at the municipality level.

Table 3-5 Summary of provincial level Financial Incentives in Canada

Province	Residential				Commercial			
	Tax	Loans	Grants	Rebates	Tax	Loans	Grants	Rebates
Alberta		✓		✓				✓
British Columbia		✓	✓	✓				✓
Manitoba		✓		✓		✓		✓
New Brunswick		✓						
Newfoundland and Labrador		✓		✓				✓
Nova Scotia		✓		✓				✓
Nunavut		✓		✓				✓
Ontario	✓	✓		✓		✓		✓
Prince Edward Island		✓	✓					
Quebec	✓	✓					✓	
Saskatchewan		✓	✓	✓			✓	✓
Yukon		✓		✓				✓

3.5 Effectiveness of Financial Incentives

The evaluation of FIs in the Canadian context can be examined by a comprehensive review of research performed in Canada and other countries. Research review revealed four major classifications criteria of FIs' effectiveness evaluation that are explained in the following sub-sections. The summary of publications on FI used in GB are provided in Appendix A, Table A4.

3.5.1 Time of evaluation

The time of evaluation of FIs divides the analysis methods into the either ex-post or ex-ante analysis. The ex-post analysis evaluates the effect of energy efficiency interventions over time and provides empirical results. The ex-ante analysis forecasts the impacts of incentives before they are implemented and give expected results [187,188].

Ex-ante analysis for FIs related to energy efficiency is usually based on engineering economics. Some researchers have shown that ex-ante analysis results tend to be over-optimistic compared to more realistic results from the ex-post analysis [127,189,190]. In contrast, Lang and Siler [191] did not find overoptimistic results from the ex-ante analysis. Over time the researchers' focus has shifted from ex-ante towards ex-post analysis, possibly due to the accountability of institutional behavior and accurate ex-post analysis results [192]. However, the ex-ante analysis can help reduce risks related to the resources used to implement FIs, provided suitable assumptions are made for analysis. Details of some of the most common methods are provided in **Table 3-6**.

Ex-post analysis can be conducted through five major methods [78]: a top-down approach, bottom-up approach, an amalgamation of top-down and bottom-up approaches, econometric modelling and policy theory. Among these methods, econometric modelling has been most extensively applied and used to study the diffusion of energy conservation technologies, free-riding effect and comparing FIs [193–198]. However, econometric modelling methods are expensive to implement and need specific data. Other ex-post analysis methods include the use of Panel Data Models [53], Data Envelopment Analysis [199], Life Cycle Assessment (LCA) [200] and Grey Model (GM) [201].

Ex-ante analysis can be conducted through two major methods: forecasting and backcasting. Forecasting methods are based on bottom-up energy-economy models and are more common in effectiveness evaluation studies. Energy-economy models can be categorized into four types: simulation, optimization, accounting and hybrid models [202]. The majority of these models are being used to determine the impact of policy instruments on building energy cost, use and emissions [202–206]. Among these models Canadian Integrated Modelling System (CIMS) is specially designed for Canadian building stocks and can determine the interaction between energy supply and macroeconomic performance. The backcasting method, as opposed to the forecasting method, is capable of determining the path needed to achieve the desired target [207,208]. In short, both ex-post and ex-ante methods have their strengths and weaknesses and lessons learned from these methods can help in obtaining FIs with desired effectiveness.

3.5.2 Stakeholders' perspectives

The optimal energy performance of a building will vary from different stakeholder's perspectives [209]; hence, the evaluation of FIs from different perspectives will provide different results. Stakeholders for an energy efficiency program include program administrator (e.g. utility), government, society or the end-users. It is quite possible that an incentive has high effectiveness

Table 3-6 Ex-ante and ex-post methods for Financial Incentives effectiveness

Evaluation	Approach	Method	Advantage	Drawbacks	Ref.
	Top-down approach	Aggregation of different indicators in achieving the target is made by assuming that the amount of energy efficiency is constant over period of evaluation. The amount of energy used with the application of instruments is compared with the energy efficiency baseline and gives the energy saved	Less time consuming	Not possible to assess the impact of individual instruments	[78,210]
	Bottom-up Approach	Effects of individual instruments are assessed to determine the impact on energy target achievement	Easy to identify the performance of the individual instrument in kWh, GJ etc.	Difficult evaluation in case of instruments assigned in packages	[78,210]
Ex-post	Combination of Top-down and Bottom-up Approach	Two methods (Top-down and Bottom-up Approach) are combined to assess the impact on energy targets	Weaknesses of top-down and bottom approach methods are covered.		[78,211]
	Econometric Modelling	Based on a statistical analysis of factors that can potentially affect the instrument evaluation			[78,156,196,197,212]
	Policy Theory	Complementary method to top-down, bottom-up and econometric modelling with particular emphasis on bottom-up approaches Policy Theory is also called Logic Model Analysis, Intervention Theory, Theory-Based Approach, Realistic Evaluation Theory or Program Theory	A comprehensive evaluation of the whole policy implementation process. Easy to identify factors impacting success or failure of incentive		[78,213]

Evaluation	Approach	Method	Advantage	Drawbacks	Ref.
Ex-ante	Forecasting (Energy Economy Models)	Energy-economy models are developed based on robust economic and engineering principles and determine impacts of FIs on the energy savings or reduction in carbon emissions Four main methods are used for generating these models: (1) (Market) Simulation (2) Optimization (3) Accounting (4) Hybrid Models Several models are developed and extensively used depending upon the evaluation goal. Examples of some of these methods are: Canadian Integrated Modelling System (CIMS) National Energy Modeling System (NEMS) Long-range Energy Alternatives Planning (LEAP) MARKet Allocation (MARKAL)	Capable of identifying the best combination of energy efficiency improvements needed under cost and time constraints CIMS hybrid energy-economy model capable of determining the interaction between energy supply and macroeconomic performance NEMS model provides long term projections of energy technologies based on operating and investment costs LEAP is capable of analyzing both economic and environmental impacts MARKAL is a bottom-up energy-based model that can determine the evolution of end-use energy systems	It can be restricted to a specific region and sector	[202–206]
	Backcasting Analysis	A future can be achieved by exploring scenarios that give the desired target	The process involves methodological steps that have sequenced order that varies with a specific backcasting approach	A conventional backcasting method is applicable to long term analysis only	[207,208]

from an end-user's point of view but has low effectiveness from the society's or program administrator's perspective. Researchers have evaluated effectiveness from the end-users, society and government perspectives [77,78,194,195,198,214–218]; technical, program administrator and multiple stakeholders perspectives [75,219–225]; and micro-economic (end-users) and macro-economic (societal) perspectives [226,227].

3.5.3 Intended target of FIs effectiveness

The effectiveness of a FI can be defined as the degree to which it contributes to the achievement of the intended target of FI [228]. The effectiveness value can help decision-makers in justifying the continuation of investment in GB incentives by the stakeholders [18]. Depending on the intended goal of the FIs, studies on the effectiveness of FIs of GBs can be broadly categorized into two groups: environmental effectiveness and cost-effectiveness. **Table 3-7** shows some common models used to evaluate FI effectiveness. Environmental effectiveness can be defined in the same manner Jurušs and Brizga [229] defined tax incentives effectiveness, i.e. the degree of achievement in terms of pollution mitigation targets, technical innovation or substitution of existing products with a more environmentally friendly product. Environmental effectiveness is an important parameter that can also help assess the rebound effect due to incentives [230]. Cost-effectiveness is a common parameter used in engineering economic evaluations of FIs.

Harmelink et al.[78] defined cost-effectiveness as the result of the application of a policy instrument to the finances needed to achieve the desired target. Cost-effectiveness results impact energy policy, program design and budget allocation [219]. **Table 3-8** provides an overview of different parameters that need to be considered for evaluating cost-effectiveness from different perspectives.

Cost-effectiveness from end-user perspectives is concerned with the direct benefits and investments related to energy saving measures [78]. Some studies on end-users cost-effectiveness have also included the change in building sales value or rent ability in the evaluation [231–234]. Some studies found that subsidies and taxes are highly cost-effective from an end-users' perspective while costs on emissions are not; however, from a societal perspective, costs on emission (carbon taxes) have high cost-effectiveness while tax credits and subsidies have low effectiveness [127,226].

Table 3-7 Effectiveness Models for FI

Effectiveness type	Model	Ref.
Environmental	Specific environmental target in comparison with that achieved by an alternative FI	[197,235–237]
Emission reduction	Reduction in CO_2 emission (tCO_2)	[75,197,217,228,238]
Energy	$E_{Eff} = 100X\frac{(PE_{ex-ante} - PE_{ex-post})}{PE_{ex-ante}} = \frac{\Delta PE}{PE_{ex-ante}}$ (%) where: E_{Eff}=Energy effectiveness PE= Primary Energy Demand	[239]
Eco-logical cost	$ECE = \frac{C_f}{V_E}$ where: ECE= Eco-logical cost effectiveness C_f=financial costs of energy upgrade (Cost/m^2) VE=reduction in environmental impact due to energy upgrade (Pt/m^2) Pt= LCA eco-indicator point	[234]
Cost	$C_{Eff} = \frac{\text{program effects in physical terms}}{\text{costs (e.g. CAD\$)}}$ where: C_{Eff}=Cost-Effectiveness	[240]
	%-age reduction in PBP where: PBP= Payback Period	[51,54,241,242]
	Benefit-to-cost Ratio (B/C)	[127,219,222]

Table 3-8 Cost-effectiveness for different perspectives

Parameter	End users perspective	Society perspective	Government perspective	Ref.
Costs	Additional costs to be paid by people responsible for energy saving measure implementation compared to a reference case	-Costs to be incurred by society compared to the reference case. -Societal cost-effectiveness	Amount spend by the government in the form of both financial and non-Financial Incentives provided to end-users	[78,219]
Time	Actual costs at time of payments	Longer time frame with discounted costs evaluation	Longer time frame with discounted costs evaluation	[78]
Indicators	-Simple PBP -Investment profit -Marginal costs -Cost of saved energy -Benefit-to-cost Ratio (B/C) -Change in LCC	-Total costs per unit of energy saved -Program costs per unit of energy saved -FI per unit of energy saved -Fiscal environment -Non-energy impacts (e.g. health and welfare)	-Total costs per unit of energy saved Program costs per unit of energy saved -FI per unit of energy saved	[219]

Limited studies have measured both the environmental effectiveness and cost-effectiveness of FIs. Most studies either focused on a single energy upgrade (example: natural gas furnace, electric appliances); a single incentive (example: rebate, tax); or from the end-users perspective [50,230]. The most comprehensive study on multiple targets was performed by Ürge-Vorsatz et al. [127]. The review study compared 20 policy instruments that had been evaluated in 60 different ex-post evaluation studies. In order to enable ease in comparison, three qualitative scales (High, medium and low) were applied for cost- and environmental effectiveness [127] (**Figure 3-4**).

Appraisal results on societal level showed that carbon tax had low environmental and cost-effectiveness; capital subsidies, grants and soft-loans had high environmental-effectiveness but low cost-effectiveness; whereas, tax-exemptions had both high environmental and cost-effectiveness among the FIs [127]. Similar comparison plots are needed for end-users and government perspectives.

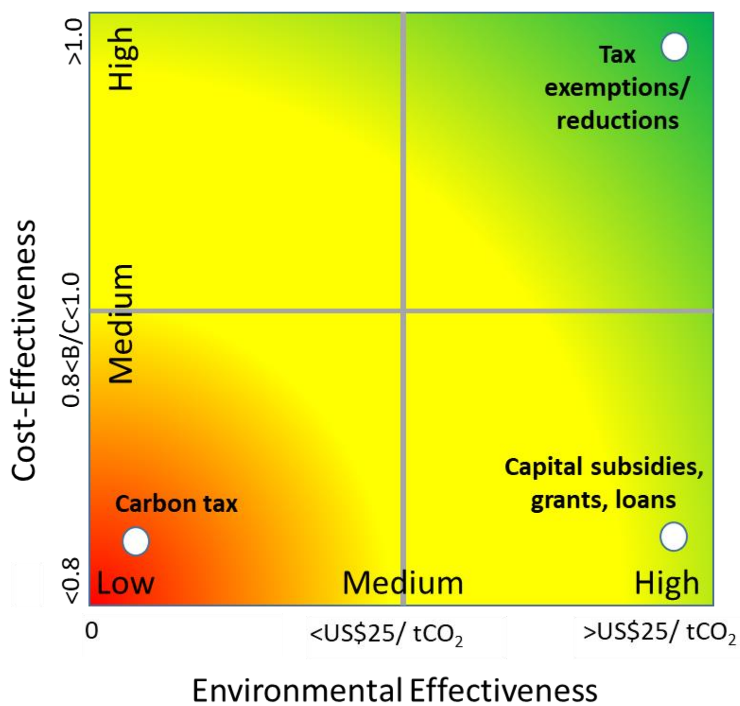


Figure 3-4 Environmental cost-effectiveness from a societal perspective (*Source*: [127])

3.5.4 Barriers to the success of financial incentives

Despite the proven advantages of FIs [75,212] a number of barriers are present that reduce effectiveness. **Table 3-9** describes some major barriers affecting effectiveness. These are split-incentives, weak incentives, time of implementation, negative impacts of FIs interaction, behavioral impacts and others. They are briefly explained as follows.

Table 3-9 Barriers to the success of different FIs

Barrier/Anti-incentive	Description	Ref.
Split incentives	Particularly important in rental housings where interests of two parties conflict and neither the landlord (due to low ROI) nor the tenant (high initial costs) wants to invest in an energy efficiency upgrade	[168,243–245]
Negative impacts of FIs interaction	Mitigating impacts are negative interaction between two policy instruments that result in reduced savings	[246–249]
Weak incentives	Lack of attractive amount of incentive and connection between the government budget and the energy target needed to be achieved by FIs	[76,78,244,250]
Time	Application of FIs at wrong time	[251]
Behavioral impacts	-Low priority towards energy efficiency (Low resource consumption culture present in most developed countries makes it difficult for FIs to be successful) -Free riders (Free-riders are consumers who would have performed energy upgrade regardless of the introduction of FIs.) - Non-takers (Non-takers are consumers who do not perform energy upgrade even with the introduction of FIs) -Rebound effect (Rebound effect results in less energy savings compared to expected due to introduction of FIs and is a source of energy efficiency gap)	[78,195,198,212,218,225,230,250,252]
Other Barriers	-Tax exemptions -High initial investment -Long payback periods -Transaction costs -Limited incentives for large buildings -Lack of information -Lack of technical expertise	[76,78,230,244,250,252–254]

<u>*Split incentives:*</u> Split incentives are a common barrier that results in the ineffectiveness of FIs in the rented residential and commercial buildings [167,168,245]. This barrier occurs when the benefits and costs are not equally distributed among stakeholders resulting in an unwillingness to invest in expensive technological options [94,168,245,255]. Split incentives can lead to underinvestment in the energy efficiency programs offered by utilities and government [168,245] or a performance gap between the energy model and the actual building energy use in non-domestic buildings [243]. Charlier [168] suggested the introduction of Energy Performance Contracts (EPCs) as a solution to this problem. As urbanization in major cities continues to

increase and trends of high-rise apartment buildings continue in Canada [172], special efforts are needed for removing split-incentives from buildings.

Weak incentives: Weak incentives are another common problem that results in low cost and/or environmental effectiveness. Weak incentives discourage investors from making energy efficient choices even if the investment is cost-effective over time for the end-users or society [76,156]. The unclear benefits associated with weak FIs and consumers preference for immediate savings lead to low confidence in making energy efficiency choices [76,256,257]. Weak FIs can also occur due to a low incentive amount than needed to achieve the desired target [132,156,258].

Time of implementation: Provision of FI at a suitable time is important to achieve full sustainability targets. For instance, incentives such as investment tax credits are attractive for building users; however, when applied during the buildings' operation period, the replacement of building equipment (old appliances, furnaces or/and HVAC systems) may occur prior to the end of useful life. This will offset the maximum possible sustainability targets. On the other hand, the application of utility rebate incentives during a buildings' operation time will encourage the use of equipment to their full useful life and meet sustainable goals of equipment energy upgrade [251]. Similarly, the local socio-economic conditions will affect the type of FIs that needs to be deployed. For example, currently (under COVID-19 situation), retrofit of buildings is seen as a solution to economic revival and sustainability [79], more FIs related to building retrofits will be needed.

Negative impacts of FIs interaction: A number of FIs and policy instruments are present for energy savings in buildings and it is important to understand how they will interact with each other and impact effectiveness. Interaction effects are influenced by the policy instrument steering mechanism, scope and timing of implementation [246,259]. This interaction can result in either positive, neutral or negative impact on effectiveness [246,259]. For example, Boonekamp [247] showed negative interaction between energy taxes, subsidies and regulations in the Netherlands that resulted in 13-30% less effectiveness compared to the sum of effectiveness for individual instruments. Despite the importance of interaction between FIs and other instruments, there are scant studies addressing the problem [246–249]. **Table 3-10** shows interaction among instruments for a study performed by Rosenow et al. [249]. More studies are needed on interaction, especially in the Canadian context.

<u>Behavioral impacts:</u> Behavioral impacts are often complex and constrained by the type of adopter (free riders, switchers and non-takers) and social, economic, physical parameters [260]. Free riders and rebound effect are most common behavioral impacts [195,198,218,225,230,237,261,262].

Table 3- 10 Interaction Matrix between financial and non-financial policy instruments

	Financial Incentives				Other Policy Instruments			
	Tax rebates	Low-interest Loans	Grants	On-Bill Finance	Carbon Tax	Building Standard	Eco-Labelling	Regulations
Tax rebates		✗	✗	*	✓	✓	✓	**o**
Low-interest Loans			✗	✗	✓	✓	✓	**o**
Grants				✗	✓	✓	✓	**o**
On-Bill Finance					✓	✓	✓	**o**
Carbon Tax						✓	✓	✓
Building Standard							✓	**o**
Eco-Labelling								**o**
Regulations								

Note- (✓): positive interaction; (**o**): nuetral interaction; - (✗): negative interaction; (*): information not present
Source: (adapted from Rosenow et al. [249])

Researchers have also shown that the free-ridership problem is more for energy measures that are replaced more frequently; hence, boiler incentive will have a higher number of free riders compared to FIs for insulation [252]. The energy use behavior and preferences of stakeholders also impact the effectiveness of FIs [144]. For example, a low priority may be given to energy efficiency when energy is low priced, resulting in a lower effectiveness of FIs [230,250]. Similarly, some adopters may prefer tax credit over interest-free loans [144]. In addition to these, occupant behavior is important in assessing the realistic energy savings due to energy upgrades [56,57]. For instance, Rana et al. [263] showed that energy, emission and cost savings vary for the same energy upgrades with different occupancy profiles. Hence, occupant behavior may result in either an increase or a decrease in FIs' effectiveness.

<u>Other Barriers:</u> In addition to above, researchers have also identified other barriers impacting effectiveness. These include: provision of tax exemptions [244], high initial investments [230], long payback periods [250], transaction costs (indirect costs) [264], limited incentives or large buildings [220], lack of information [76,78,230,253] and technical expertise [253,254].

3.6 Summary

A detailed literature review was performed to identify the types and quantities of FIs present for promoting GBs in Canada. This work revealed major regional variations in the FIs available for residential and commercial buildings. Loans supplied by financial institutions and rebates by utilities are the most common FIs in all provinces of Canada. Three provinces (ON, QC and BC) are leading the way in the availability and promotion of FIs for GBs construction in Canada. These provinces have FIs that ensure the penetration of energy efficient technologies and are hence paving the path towards deployment of more stringent building energy standards. Despite the presence of a number of FIs, more targeted FIs are required for low-income housing, aboriginal communities, non-profit organizations, rental housing stakeholders and heritage buildings.

In addition, published literature on FIs effectiveness also revealed that a number of factors impact the evaluation results. These factors can be grouped into four criteria: stakeholder (end-users, government, society, etc.) perspective considered, time of evaluation (ex-ante and ex-post), type of incentive (subsidy, rebate, dis-incentive) and the intended target. There also exists a non-uniformity in the definition of effectiveness, as well as the methods and models used for evaluation. These differences make it difficult to compare evaluation studies and make conclusive decisions. A deeper understanding of the interaction between different policy instruments, investor behavior and preferences of targeted stakeholders is essential to remove barriers and ensure the success of FI. There is also a need for more comparative studies on FIs effectiveness from different perspectives (end-users, society and government) using ex-ante and ex-post evaluation approaches.

Chapter 4 Impacts of Occupant Behaviour on Incentive Policies

Parts of this chapter have been published in the Elsevier *Journal of Cleaner Production*, as an article titled “Occupant-based energy upgrades selection for Canadian residential buildings based on field energy data and calibrated simulations” [263].

4.1 Background

A growing body of literature recognizes occupant behaviour (OB) as the major reason for a gap between actual and simulated energy use of a building [56,57]. OB is a major area of interest within the field of building energy performance. OB includes occupancy, occupant movement and interactions with the building’s systems and appliances [58]. Ignoring the impact of OBs can over predict energy savings or increase the energy use up to 80 % even in identical homes [265] [59] [266–270]. Furthermore, researchers agree that for energy efficient residential buildings, such as net-zero energy houses, OB's influence in BES will become even more significant [60,271]. Since OB results in a significant impact on energy use, it is vital to understand occupancy implications on the selection of suitable EPUs.

Detailed monitoring studies further affirm the significance of OB for obtaining realistic BES results. In contrast to commercial buildings, limited research works are focusing on the effects of OB in residential buildings [62]. There remains a paucity of energy models based on monitored data [61,62]; and, consequently, a limited understanding of the impacts of OBs on EPU selections. In Canada, energy monitoring studies on residential buildings have mostly focused on old buildings constructed prior to implementation of the current more stringent building energy codes, such as NECB-2015, BC Energy Step Code 2017. Saldanha and Beausoleil-Morrison [60] focused on residential buildings in Ottawa, Ontario, constructed between the 1930s and 1990s. A recent energy-monitoring study on Gemini home, Toronto, Ontario, is performed on a retrofitted home originally constructed in 1879 [272]. Other studies have generated energy models based on data collected through interviews and surveys [273,274]. Results from survey studies are able to present impacts of occupant behaviour but are unable to provide a good prediction of occupant behaviour on energy savings due to EPUs [275,276]. To date, there are few studies that have investigated the association between the impacts of occupants on energy savings using calibrated energy models.

Hence, there is a need to determine the influence of occupant behaviour on energy use along with the consideration of occupant choice and limitations to make informed decisions.

This chapter's main objective is to investigate the possibility of catering to the energy demand of a new residential building according to expected occupant behavior (specifically occupancy profile) and compare energy performance upgrades that can reduce this energy demand. To meet this objective, a decision support methodology is developed that ranks the best energy performance upgrades for a specific occupancy profile. The methodology is demonstrated for two single-family residential buildings as a case study in Canada.

4.2 Methodology

In this chapter, a methodology is developed to identify the most appropriate energy performance upgrades for new residential buildings with expected occupancy profiles. The methodology shown in **Figure 4-1** has two main phases: (1) Data Collection and (2) Data analysis.

4.2.1 Data Collection and Processing

The two key sources of data include: (1) literature-based data used to identify potential energy upgrades; and (2) data captured from the field monitoring system to create calibrated energy models. The main sources used for literature were peer-reviewed articles and technical reports related to residential building energy and cost modelling. A thorough literature review was performed for current building energy standards for residential buildings, energy and cost modelling methods, energy monitoring techniques, occupancy profiles and energy performance upgrades possible for residential buildings. Energy performance upgrades can be categorized into three categories: (1) passive, (2) active and (3) renewable energy upgrades. MCDM methods available for ranking and prioritization of energy upgrades were also explored. The collected information was used for developing preliminary energy simulation models, calibrating and validating models, analyzing the effects of energy performance upgrade combinations, assessing associated life cycle costs, PBT and GHG emission reductions and finally prioritizing the most appropriate upgrades for a specific occupancy profile.

The intrusive load monitoring (ILM) method is proposed for collecting energy use data related to the occupancy profile. ILM method monitors energy use through individual devices with sensing monitors distributed within the building [277]. Contrary to the non-intrusive method, the data

GHG	IC	PBT
1	0	0
2/3	1/6	1/6
1/2	1/4	1/4
1/3	1/3	1/3
0	1/2	1/2

Note-GHG: greenhouse gases; IC: Capital Investment; PBT: Payback period; TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution; HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilator

Figure 4-1 Proposed methodology on the evaluation of upgrades for SFD obtained from ILM are more accurate and helps generate better energy models. The design and installation of energy data monitoring are beyond the scope of this research work and should be designed with the consultation of building developers, owners and data monitoring experts.

4.2.2 Data Analysis

Energy modelling: A preliminary energy model was developed to determine the end-use energy demand of the residential building under study. HOT2000V15.1, a simulation tool developed by CANMET Energy Technology Center was used to generate the model. HOT2000 is tailored for residential buildings in Canada [278] and hence ideal for assessing the operational energy use of low-rise residential buildings in Canada (More details on HOT2000 can be seen in Appendix B). The data needed to generate a standard energy model includes location, house geometry, building envelope characteristics, energy systems and equipment present in the house, number of occupants and occupancy hours.

Calibration: Calibration is defined as a measure of the BES model's accuracy and ensures that the energy performance gap between simulated and the actual energy use of the building lies within acceptable limits [279]. The calibration is an inverse approximation method where the values of inputs are changed until output values are approximately similar to actual energy use [280,281]. Three most commonly used guidelines that define benchmarks for calibration are the American Society of Heating, Ventilating and Air Conditioning Engineers (ASHRAE) Guidelines 14 [282]; Federal Energy Management Program (FEMP) [283]; and International Performance Measurement and Verification Protocol (IPMVP) [284].

ASHRAE 14 requires two calibration benchmarks to be achieved for acceptable BES. If results exceed these limits, the calibrated model becomes invalid and needs to be recalibrated until the error is within permissible limits. These include Mean Bias Error (MBE) (%) and the Coefficient of Variation of Root Mean Square Error (CV(RMSE)) (%). MBE is a non-dimensional bias measure (i.e., the sum of errors) between measured and simulated data for each hour. It captures the mean difference between measured and simulated data points and is considered a good indicator of the overall bias in the model. RMSE index assesses data by capturing offsetting errors between measured and simulated data and does not suffer from the cancellation effect in MBE. The positive bias compensates the negative bias and can result in incorrect validation. Acceptable tolerance limits for the two benchmarks vary according to the type of calibration hourly or monthly and are provided in Appendix C, Table C1.

The following steps are involved in performing the calibration process:

1) Constructing an initial BES model on HOT2000 based on the engineering drawings, local weather data, occupancy, equipment specifications and indoor temperatures.

2) Adjusting constructed BES model with data obtained from monitoring and making suitable assumptions for unknown parameters.

3) Determining MBE and CV(RMSE) values on monthly energy based on results of BES model and actual energy use with *Equation 4-1(a)* and *(b).*

$$MBE\ (\%) = \frac{\sum_{k=1}^{N_p}(m_k - s_k)}{\sum_{k=1}^{N_p}(m_k)} \qquad \textit{Equation 4-1(a)}$$

$$CV(RMSE)\ (\%) = \frac{\sqrt{\sum_{k=1}^{N_p}(m_k - s_k)^2/N_p}}{\overline{m}} \qquad \textit{Equation 4-1(b)}$$

Where, m_k and s_k are the respective measured and simulated data points for each model instance '*k*'; *Np* is the number of data points at interval '*p*' (i.e., $N_{monthly}$=12) and *m* is the average of the measured data points.

4) Re-adjusting the energy model parameters until the results of the benchmark metrics are within acceptable limits of MBE and CV(RMSE) [282].

Calibrated energy models were tested for variation in energy consumption due to changes in energy upgrades. The energy consumptions under upgrades combinations were used to find the change in the house's carbon footprint and operational costs.

Life cycle costing and carbon footprint: For this study, the Net Present Value (NPV) method was used to determine the lifecycle cost analysis (LCC) for assessing building upgrades. LCC is an economic evaluation technique that determines the costs of the entire life span of a product or process [285]. Typically, LCC for buildings includes construction, maintenance, repair, replacement and disposal costs [286,287]. Previous studies on residential buildings in Canada have considered a 30-year timeline for building operation [288,289]. Therefore, the 30-year operational period was considered appropriate for the proposed methodology.

In this study the relative life cycle cost model by US Federal Energy Management Program [290] was used. Here the $dLCC_t$ is the cost difference between the life cycle cost (LCC_i) for a house with energy upgrades and the life cycle cost of a reference case (LCC_r) house. The reference case is a SFD made according to local code compliance or the status of residential building prior to any upgrades. This cost model does not require costs related to all building components but only the cost differences of the energy components that are being changed [291,292]. Cost differences associated with the additional investment, energy bills, maintenance and replacement cost, as well as end-of-life cycle costs, are considered for $dLCC_t$ calculation as indicated by *Equation 4-2(b)*.

$$dLCC_t = LCC_i - LCC_r \quad \text{(CA\$)} \qquad \textit{Equation 4-2(a)}$$

$$dLCC_t = dC_c + dC_U + dC_{EOL} \quad \text{(CA\$)} \qquad \textit{Equation 4-2(b)}$$

where, $dLCC_t$ = difference in total life cycle costs of SFD with upgrades and base case, LCC_t = total life cycle costs of house with energy upgrades, LCC_r = total life cycle costs of reference house, t = Study period in years; dC_C = difference in costs of SFD with upgrades and base case; dC_U = difference in costs in the use stage (operational energy use, maintenance and replacement costs) of SFD with upgrades and base case; and dC_{EOL} = difference in costs of the end-of-life of SFD with upgrades and base case. The end-of-life cycle costs were considered negligible for determining LCC.

Carbon footprint is defined by the total GHG emissions and is usually expressed in units of carbon dioxide equivalent (CO_2-eq) [293]. Energy-based GHG reduction is dependent on the grid emission factors and the quantity of energy demand reduced through the application of EPUs. Grid emission factors are dependent upon the source of energy production and will change with the location of the building [294]. Energy results from the calibrated energy models were used to calculate the long-term GHG impacts of the occupancy profile under the application of EPUs. *Equation 4-3* is used to calculate the GHG emissions associated with energy fuel consumption, where the emission factor changes with the type of fuel.

$$GHG_f = EF_f \times F_f \qquad \textit{Equation 4-3}$$

Where, GHG_f is greenhouse gas emission rate of fuel f consumed (kg CO_2-e), EF_f is the emission factor for energy source (natural gas or electricity) while F_f is the annual energy consumed for operating the house equipment and systems.

4.2.3 Ranking Upgrade Scenarios

The selection of suitable EPUs is governed by a number of conflicting parameters that include: energy performance, environmental impacts, economic requirements, regulatory and social aspects [295]. The decision-maker has to arrive at a compromise among these parameters when selecting the EPUs. Multi-criteria decision-making (MCDM) methods help solve this problem and prioritize and rank the most desirable alternatives [296]. MCDM can treat qualitative and quantitative criteria and come up with a ranking of alternatives [297].

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the most well-established multi-criteria methods that is used to test competing alternatives [298,299]. By using the TOPSIS method, the solution that is the nearest to the ideal among all the sets of alternatives is selected. The method has been successfully used in previous studies for selecting the best energy upgrade [300–303]. Therefore, the TOPSIS method was considered appropriate to meet the goals of this study.

The following steps are involved in performing the TOPSIS technique for this particular methodology.

1) Construction of the decision matrix and weighting matrices. The decision matrix considered 3 criteria: reduction in GHG emissions (kg CO_2-e), initial investment (CA$) and payback period (Years). The weighting matrix is generated by defining five weighting schemes (**Table 4-1**) representative of investors' preference for pro-environmental or pro-economic investments.

In the pro-environmental option, more weight is given to the reduction of GHG emissions, while for a pro-economic option lowest LCC is given maximum weight normalization of the decision matrix through the conversion of different criteria into non-dimensional values using *Equation 4-4*.

$$\bar{z}_{ij} = z_{ij} \Big/ \sqrt{\sum_{i=1}^{j} z^2{}_{ij}}\text{; for i= } \overline{1,n} \text{ to j=} \overline{1,m} \qquad \textit{Equation 4-4}$$

Where, "z_{ij}" is an entry in the decision matrix and m represents the total number of rows and n represents the total number of columns.

Table 4-1 Criteria weights for different occupant preferences

Selection Criteria	Description				
	Pro-Environmental	Higher weightage for environment	Equal importance	Higher weightage for economy	Pro-Economic
GHG emission reduction (kg CO_2-e)	1	2/3	1/3	1/6	0
Capital Investment (IC)	0	1/6	1/3	1/6	0
Payback Period (PBT)	0	1/6	1/3	2/3	1

Generation of the weighted matrix through multiplication of weights of each criterion with entries in normalized matrix.

2) Determination of the best and worst alternatives for each criterion.

The best solutions (V_b^+)for the weighted normalized matrix are selected out of all alternatives:

$$V_b^+ = [\text{Max}_{GHG}, \text{Min}_{IC}, \text{Min}_{PBT},]$$

The worst solutions (V_b^-)for the weighted normalized matrix are selected out of all alternatives:

$$V_b^- = [\text{Min}_{GHG}, \text{Max}_{IC}, \text{Max}_{PBT},]$$

3) Calculation of distance from ideal solution using Euclidean distance.

The distance of the alternative from the positive ideal was found by using *Equation 4-5(a)*and for the negative ideal using *Equation 4-5(b)*.

$$d_i^+ = \sqrt{\sum_{j=1}^{m}(v_{ij} - V_b^+)} \qquad \textit{Equation 4-5(a)}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}(v_{ij} - V_b^-)} \qquad \textit{Equation 4-5(b)}$$

The relative closeness to the ideal solution was found by *Equation 4-5(c)*

$$CL_i^* = {d_i^-}/{d_i^- + d_i^+}$$ *Equation 4-5(c)*

4) Ranking the alternatives based on relative closeness to the ideal solution.

4.3 Methodology Demonstration

4.3.1 Study Area

A case study approach is taken to apply and demonstrate the methodology using field data obtained from two living laboratory houses located in Kelowna city, Okanagan Valley (Canada). Although other living laboratories are present in Canada, including the Canadian Centre for Housing Technology (CCHT) houses in Ottawa [304] and the Archetype houses near Toronto [305], these living labs are the first of their kind in Canada conforming to the Okanagan region construction practices. The two houses are located in one of the fastest growing areas in Canada, the Okanagan Valley (**Figure 4-2**).

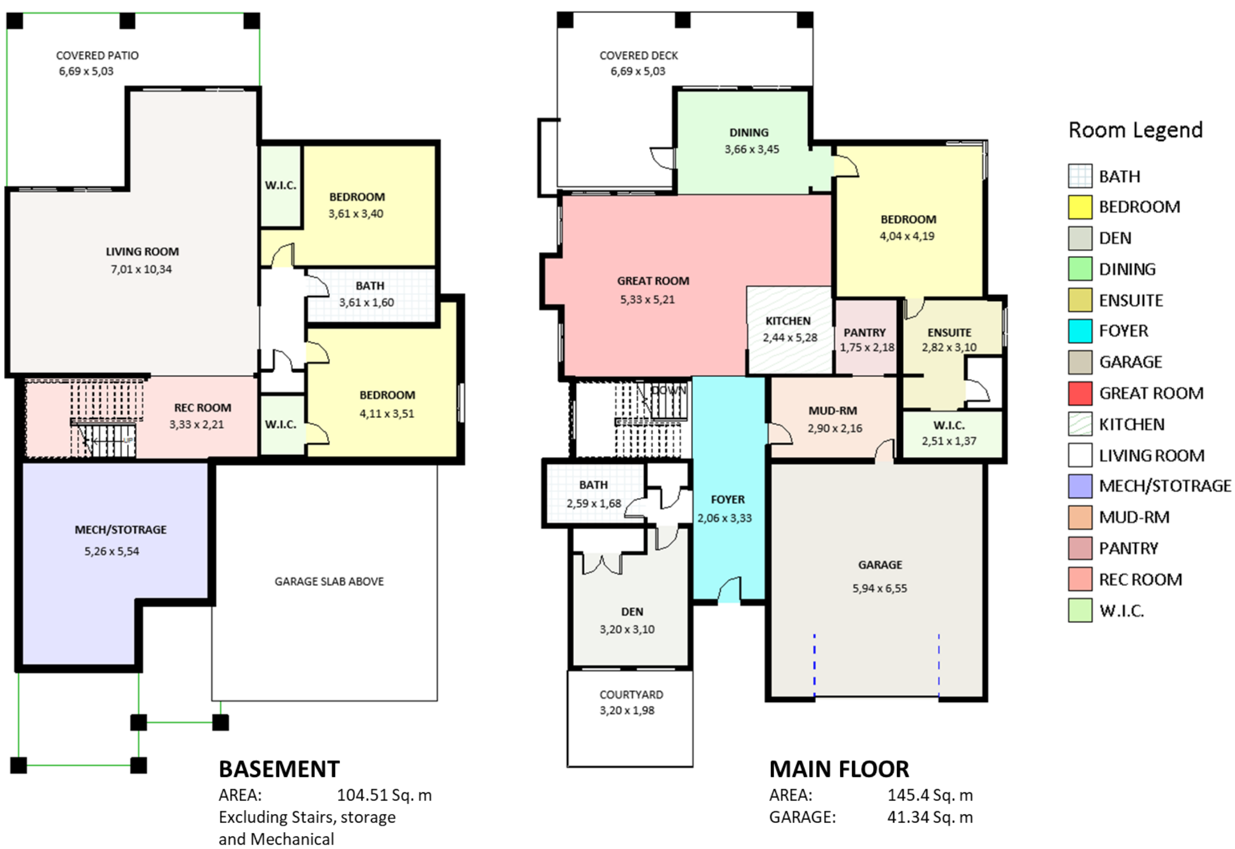


Figure 4-2 Floor plans of case study homes

The case study homes were constructed in 2016 and occupied in 2017. These mid-size residences are identical in their architectural design, location and orientation and are exposed to the same external features. However, the two homes vary with respect to the building envelope, heating and cooling systems and occupancies. The household characteristics for the homes are provided in **Table 4-2**. The construction materials and thermal characteristics obtained from the industrial partners were used to develop the energy model. The geometry and other relevant information of this house were extracted from the relevant drawings and bills of quantities. The thermal characteristics of specific envelope components and equipment such as HVAC, lighting and appliances were collected from the manufacturers' specifications.

Table 4-2 Household characteristics

Parameter	Standard Home (STH)	Advanced Tech Home (ATH)
Occupancy Profile	2 working adults (aged 35-49) 2 teenagers (aged 15-19)	 retired couple (aged 50-64)
Total area of the building	291.25	291.25
(m^2)	249.91	249.91
Gross floor area (m^2)	364.57	364.57
Area of walls (m^2)	6.60	6.60
Area of doors (m^2)	57.91	57.91
Area of windows (m^2)		
Space cooling and heating (HVAC)	Payne (PG92SCS) 17.58 kWh AFUE 92.1% Natural Gas & Payne (PA14NC) 9.96 kWh 14 SEER Split A/C	5 series (500A11) – Geothermal c/w ECM variable speed blower (Heating 4 COP, Cooling 5.6 COP)
Domestic hot water (DHW)	Standard DHW system, 227 litres, EF 1.901, Electricity-based	GeoSpring™ hybrid electric water heater, 303 litres, EF 3.14, Electricity-based
Wall-Insulation (WL)	USI 0.28 Batt (Eff. USI 0.32)	9.525 mm EPS Styrofoam & USI-0.28 Batt (Eff. USI 0.27)
Celling- Insulation (RF)	USI 0.26 Batt, USI 0.14 blown (Eff. USI 0.14)	USI 0.28 Batt, USI 0.11 blown (Eff. USI 0.09)
Foundation (FN)	USI 0.26 Batt (Eff. USI 0.32)	ICF blocks (Eff. USI 0.25)
Windows (WN)	Vinyl double glazed windows c/w 180 low-E	Vinyl triple glazed windows c/w 366 low-E
Appliances (APP)	Standard Appliances: Dishwasher, washer & dryer, fridge, oven and hood fan	Energy-Star Rated Appliances: Hood fan with LED lighting and ultra-quiet blower, dishwasher, heat pump dryer and washer, 5 door fridge, double ovens
Lighting (LED)	Incandescent bulbs	LED bulbs
Solar (PV)	None	10 panels (16.3 m^2) azimuth 15' and slope 25'

The case study homes cover an area of 291.25 m^2 and consist of two storeys, the main floor and a partially underground basement. One house called Standard Home (STH) is built by following the BC building code 2012 [306] represents typical construction practices such as standard building characteristics, building systems and appliances. It represents the base case scenario for this study. The other home, called Advanced Tech Home (ATH), is representative of an energy efficient home and is constructed with the most energy efficient materials and systems locally available in Kelowna (Okanagan Valley). In addition to having higher fabric insulation (higher insulation and foundation made of insulated concrete forms- ICF blocks), better performance windows (Vinyl triple glazed windows c/w 366 Low-E), an HVAC system consisting of a geothermal heat source pump and energy star rated appliances the ATH is supplied with renewable energy from a solar (PV) system installed on the roof.

The two houses represent occupancy profiles most common in Canada: (a) a family with dependent children where the parents work full time; and (b) a retired elderly couple who spend most of their time indoors. The two profiles are representative of 52.3% of Canadian private household structures with couples with children (Occupancy Profile 1 for this study) representing 26.5% and couples without children (Occupancy Profile 2 for this study) representing 25.8% [307].

Canada does not have a mandatory retirement age though the average age of retirement for most Canadians is 63.5 years [308]. Since it was known that the residents pertaining to Occupancy Profile 2 are retired, the profile is called retired couple for this study.

The STH model has previously been used in the study by Perera et al. [303] for assessing household and transport incentives for clean energy. This study extends the original model by calibration and considering additional EPUs. The detailed monitoring ensures a more realistic representation of occupants' behavior and savings from energy upgrades. In order to make a comparison between the influence of two occupancy profiles on energy and GHG reduction potential of various EPSs, STH was upgraded with energy upgrades present for ATH while ATH was downgraded with the standard materials, equipment and appliances present in STH.

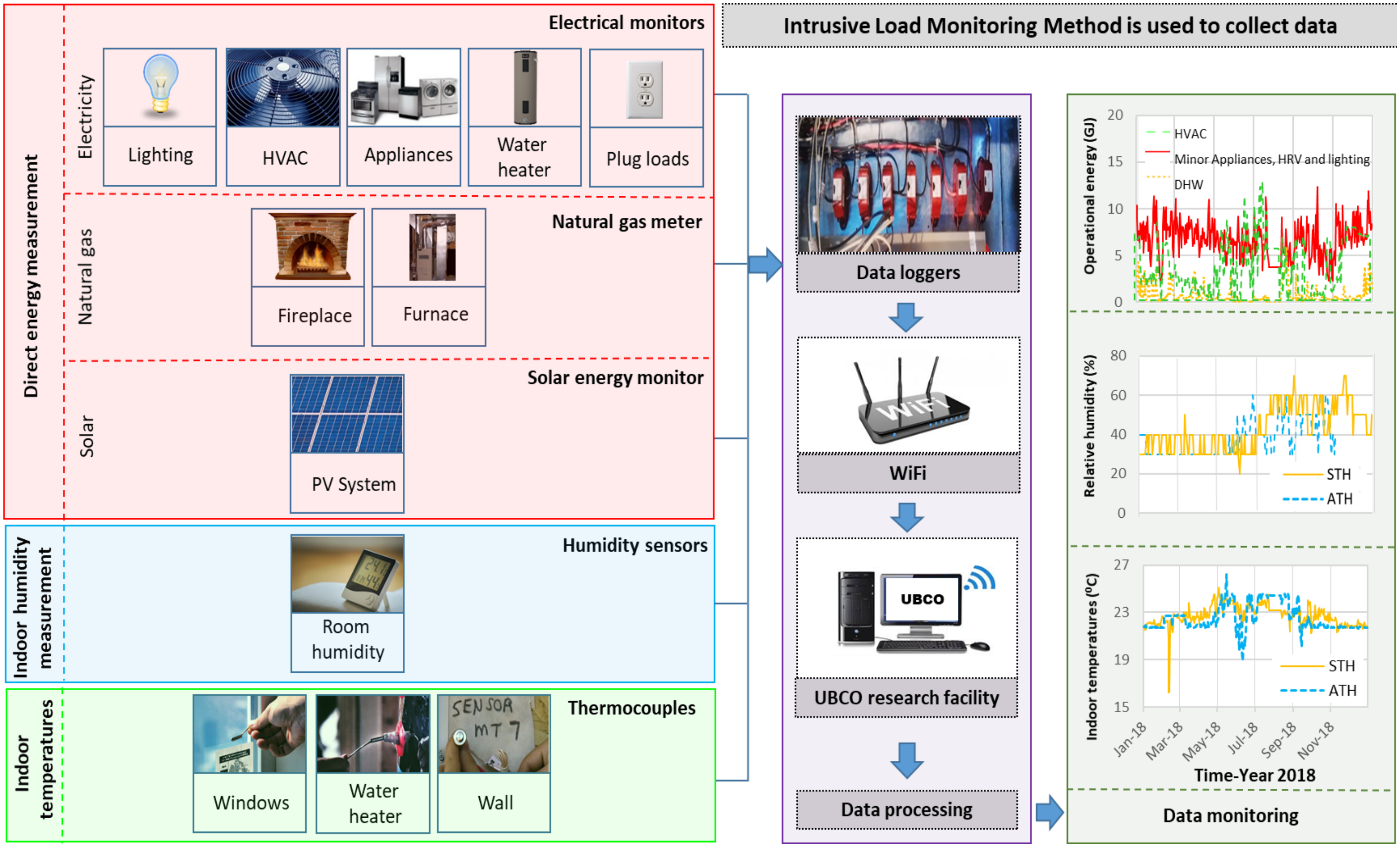
4.3.2 Energy Monitoring

An ILM method was employed for determining the energy use by various building components. The living laboratory was installed with temperature, humidity sensors as well as with electricity and natural gas consumption monitors. The system architecture of the data monitoring and acquisition system is shown in **Figure 4-3**. The real-time data was captured for one-year and a comprehensive database was developed for evidence-based research. **Figure 4-4** shows the energy use pattern for the two homes' HVAC systems, minor appliances (including small kitchen appliances such as toaster oven, microwave oven, electric kettle), lighting, domestic hot water (DHW) system, laundry washer and dryer. It is observed that the energy used in appliances by the ATH is more despite being more efficient appliances. The presence of a ground source heat pump also indicates a higher use of energy during summer months as compared to a conventional HVAC system. The current research assesses monthly energy use of different systems and average temperature and humidity levels for the two homes, while daily, weekly and seasonal variations in energy use are not part of this research.

4.3.3 Energy Modelling

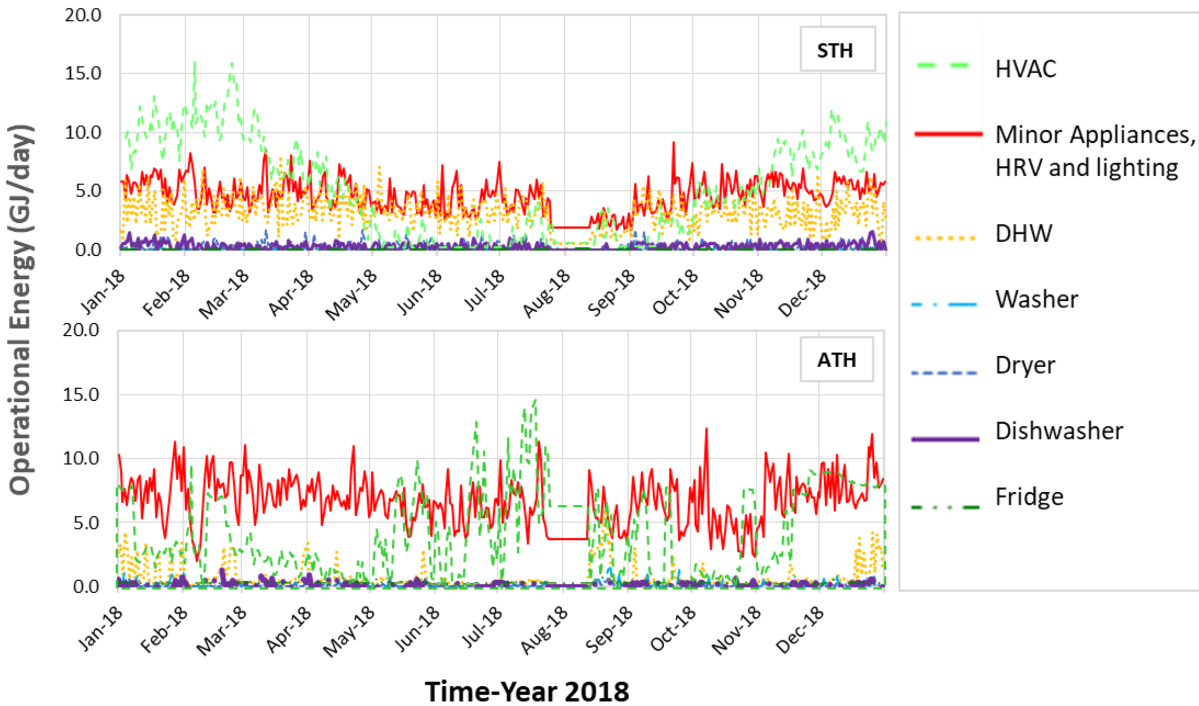
The BC Building Code-2012 and local municipality by-laws were used while designing the base-case models of the two buildings. The energy models for the two homes were generated based on the detailed drawings provided by the developer, local metrological data (Appendix H) and suitable assumptions regarding the operation of different appliances and systems. The energy models were constructed using HOT2000 version 11.7b23[309]. HOT2000 uses long term weather data in bin method and steady-state models for assessing monthly energy loads [310]. HOT2000 is used extensively for the design and certification of low-rise residential buildings in Canada [309].

To determine the error in the base case models, the monthly energy results of the simulation and monitored energy were compared using MBE and CV(RMSE) metrics [282,311]. Studies have shown that minor errors in simulated and measured energy use are due to the simplification of simulation tools, while more significant errors are due to incorrect model inputs [312]. The information used to calibrate the energy models is provided in **Table 4-3**. The base models for two occupancy profiles were constructed based on the architectural drawings provided by the developers. In this regard, HOT2000 guidelines for constructing an energy model for Canadian homes were followed. Architectural drawings and material specifications were used to develop these preliminary models.



Note- HVAC: Heating, Ventilation, and Air Conditioning; UBCO: university of British Columbia

Figure 4-3 System architecture for the Living Lab



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Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; STH: Standard Home; ATH: Advanced tech home

Figure 4-4 Trend of measured energy use in STH (top) and ATH (bottom) graph

Table 4-3 Information used to calibrate energy models

No.	Source	Description
1	Logged measured data	Lighting and general equipment electrical load data
2	Spot measured data	Measured electrical load data
3	Infiltration rates data	Air change rate from blower door test tests
4	As-built documentation	Architectural and mechanical as-built drawings
		Wall materials and constructions taken from as-built drawings
5	Standards and guidelines	BC Building Code 2012
		HOT2000 input/output reference guidelines
6	Stakeholder consultation	Validation of drawings and assumptions
7	Energy bills	Monthly energy bills collected over one year time

These models were upgraded with general information such as the number of occupants and air change rate of the home provided by energy consultants blower door tests. The missing information, such as the performance of appliances and electrical equipment, was based on the measured lighting and electrical data and initial base models generated large errors between the actual and simulated energy uses. Manual calibration was performed to decrease these discrepancies in the energy results. Most researchers use manual calibration of energy models and involve iterative adjustments until the model is validated for the specified standard [313]. For calibration first, the energy use calculated by HOT2000 was compared with the monthly energy bills obtained from the home owners. One parameter was changed at a time starting with matching performance results of equipment with monitored energy. Some of the appliances were operating for a longer duration than standard values used in energy tools. Likewise, the actual efficiency of the equipment was determined by decreasing the values compared to the manufacturers specifications. In addition, the R-values of the walls, roofs, floors and foundations were varied as the value on drawings can be changed by construction errors. Multiple trials were done by upgrading the model with field measurements until acceptable errors were obtained. The final base case models had MBE and CV (RMSE) 0.99 and 3.46 for STH and -0.06 and 0.88 for ATH calibrated models on HOT2000, respectively. It was possible to obtain low errors due to the detailed energy, temperatures and humidity data collected through the intrusive load monitoring technique.

The calibrated models were then run for different EPU combinations to determine the variation in annual energy use. A total of 514 simulation runs were performed on the nine EPU options. In order to increase the simulation time interaction impact between EPUs combinations was assumed to be negligible. The operational energy consumptions obtained from the aforementioned models upgraded with EPUs were used in the next phases to quantify the GHG emissions, operational costs and life cycle costs. It should be noted that the comparison between the validated models for the two profiles was not possible based on the calibrated models due to the difference in materials, equipment and appliances of the two homes. In order to compare the impact of energy upgrades for the two homes with respect to two occupancy profiles, the EPUs were added in STH while energy systems, equipment and appliances in ATH were downgraded with those present in ATH to find the annual operational energy, GHG emissions and LCC. Hence, it was possible to obtain the impact of occupancy profiles for the same energy systems, equipment and appliances.

4.3.4 Life Cycle Costing and Carbon Footprint

The initial construction cost of the SFD base case was estimated using RSMeans residential cost database [314], market prices of appliances, ASHRAE report on the economic database for green residential buildings [315] and data obtained from the Okanagan developers [316]. The costs obtained from RSMeans and the consultation process were adjusted to give a reasonable estimate of the Kelowna construction costs. The costs of construction were limited to additional investments for building energy upgrades. Costs relating to home insurance, landscaping, furniture, mortgage payment, government incentives for green upgrades were not considered. **Table 4-3** shows the costs associated with different energy upgrades. The maintenance period for different building systems is used as defined by Kirk et al. [317] which varies with different upgrades. Moreover, costs due to the replacement of existing systems, pollution damage and hazard prevention at the rehabilitation process were not considered for this study.

Table 4-4 Energy upgrades and associated costs

No.	Energy upgrades	Abbreviation	Type of energy upgrades	Expected service life (Years)	Annual Maintenance as a percentage of capital cost (%)	Initial cost difference CA$(*US$*)
1	Appliances[a]	APP	Active	16.5	5	3,000 (*2,130*)
2	Domestic hot water	DHW	Active	15	5	1,200 (*852*)
3	Foundation-ICF	FN	Passive	30+	_[c]	10,000 (*7,100*)
4	Space cooling and heating[b]	HVAC	Active & Renewable	15	5	9,000 (*6,390*)
5	Lighting	LED	Active	15	3	43 (*31*)
6	Solar	PV	Renewable	25	1.5	8,600 (*6,106*)
7	Roof- Insulation	RF	Passive	30+	_[c]	300 (*213*)
8	Wall-Insulation	WL	Passive	30+	_[c]	1,000 (*710*)
9	Windows	WN	Passive	40	2.8	12,127 (*8,610*)

[a] Appliances include kitchen (dishwasher, exhaust hood, stove and oven) and laundry appliances (dryer and clothes washer)
[b] HVAC systems upgrade was considered to be ground source heat pump that serves part of both heating and cooling systems of the house and involves the use of electricity for running pumps and renewable energy
[c] Maintenance and replacement of Wall-insulation, Ceiling insulation and ICF foundation is beyond the study period of 30-year

The discount rate of 3% and an inflation rate of 5% were assumed based on the literature [318,319]. The energy costs for the house were calculated using the electricity and natural gas tariff defined by the local utility providers. Accordingly, the cost of electricity was assumed as 9.845CA¢/kWh (*7.1*US¢/kWh) for the consumption up to 1600 kWh and 15.198 CA¢/kWh (*10.90* US¢/kWh) for the consumption above 1600 kWh. The cost of natural gas was assumed as 1.141 CA$/GJ (*0.82* US$/GJ) [320]. Additional charges related to electricity and natural gas supply such as customer charge, basic daily charge, delivery charge, storage and fuel transportation charges were also considered in the calculation of operational energy in the building life cycle.

Total GHG emissions of a residential building depending on the supply energy mix and the energy consumption of the residential activities. In Canada, the emission factors vary with the primary energy sources [321]. Unlike other provinces in Canada, BC has a low-emission electricity supply since the major portion of the grid electricity is hydro-based [322]. Electricity emission factor is 2.80 $kgCO_2$-eq./GJ, whereas the emission factor of natural gas is 65.75 $kgCO_2$-eq./GJ [323].

4.4 Results

The above-described methodology was used to assess the variation in annual operational energy, GHG emissions and life cycle costs associated with the application of EPUs in a single-family detached house under two different occupancy profiles. Since the operational life cycle period of 30-year was considered, only EPUs that had PBT of 30-year or less were considered for comparison and ranking. The EPUs were then ranked with respect to five scenarios representing the priority of the investor. The results of the application of the methodology for the two residential occupancies are presented in this section.

4.4.1 Occupancy Profile 1

Occupancy Profile 1 comprised four family members, including two working adults and 2 school-going children. EPUs that fulfilled the PBT limit of 30-year or less with respect to the energy savings, GHG emissions reduction and PBT are discussed in this section.

<u>Annual operational energy:</u> **Figure 4-5** depicts the energy savings possible with respect to the selected upgrades for Occupancy Profile 1. These EPUs have been distributed into four groups with respect to percentage energy savings to the initial energy use (119.33 GJ/year) of the Occupancy Profile 1. The majority of the EPUs with a PBT of 30-year provide energy savings in the range 0-20%. As expected, the upgrades yield more savings in combinations and only four upgrades, LED, RF, DHW and PV, give reasonable savings. From the chart, it can be seen that by far, the greatest energy savings are up to 71% for the combination “RF WL LED HVAC DHW PV”. Among the passive energy upgrades, wall (WL) and roof (RF) insulations yielded savings in the majority of the combinations, while among the active systems, domestic hot water (DHW) was determined to have high-energy benefits. HVAC energy upgrade yielded more than 50% in

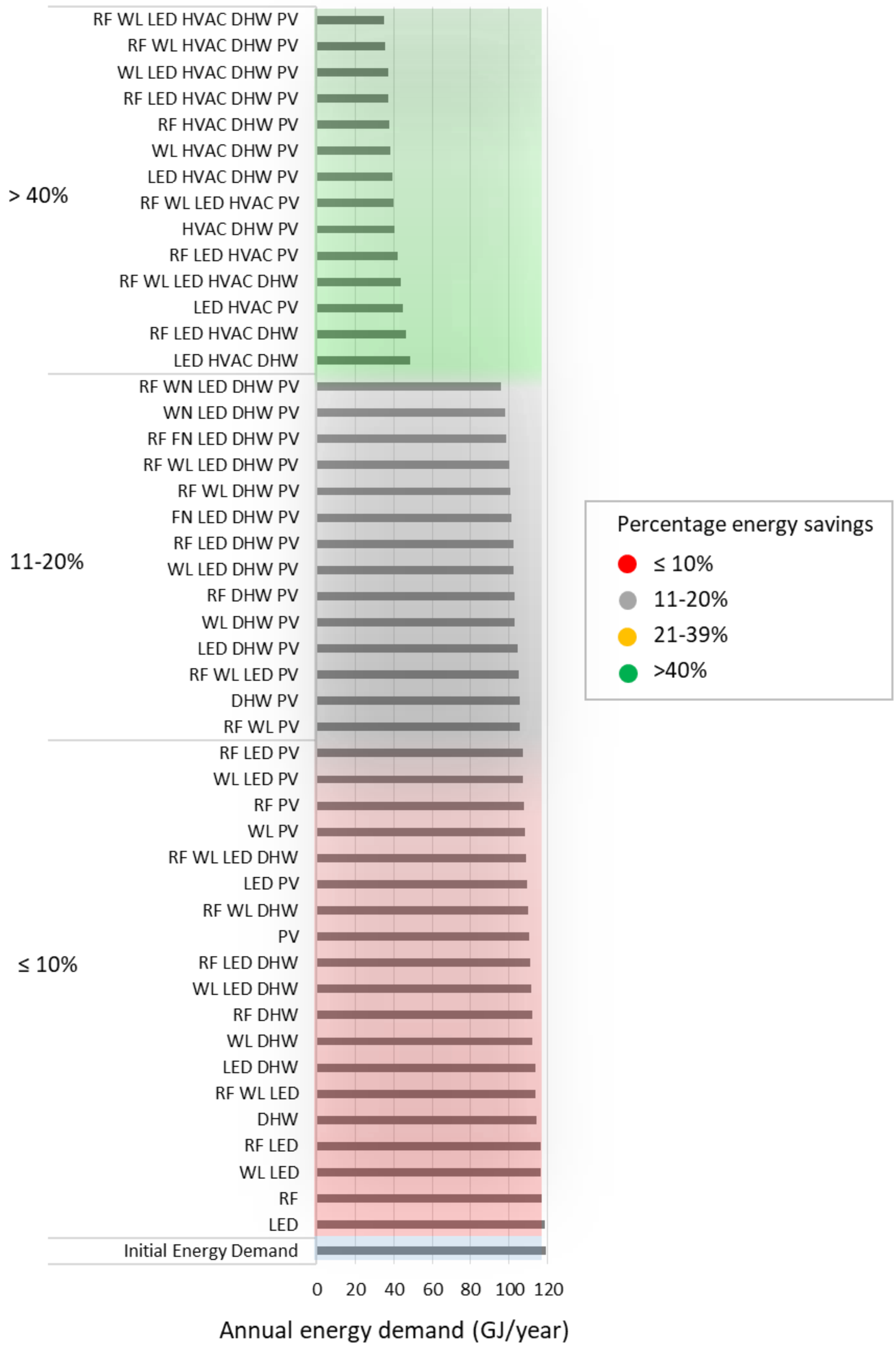
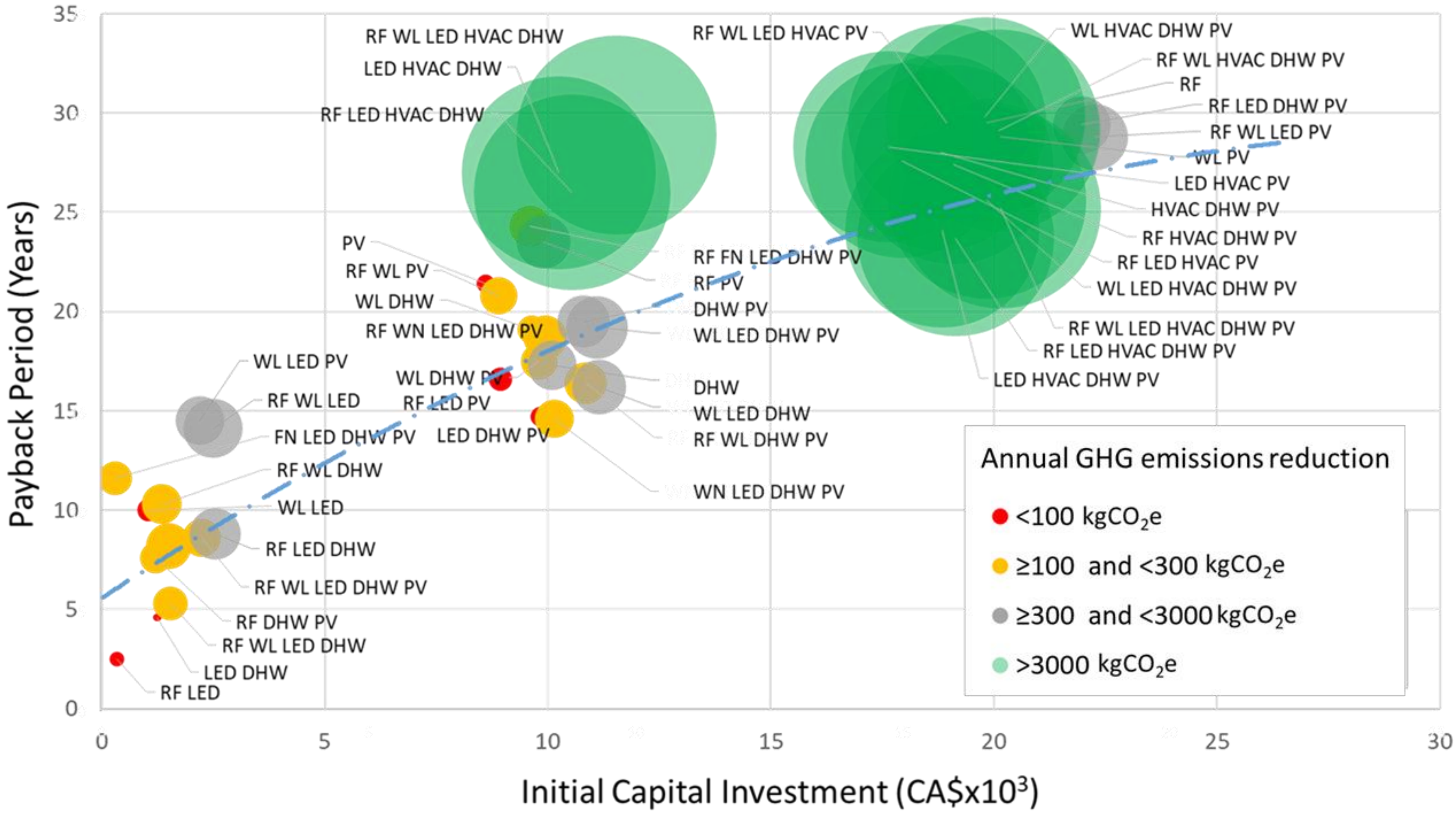


Figure 4-5 Occupancy Profile 1: Reduction in annual energy demand

operational energy savings; however, the system had a high initial cost that increased its PBT (beyond 30-year) and made this upgrade financially unfeasible.

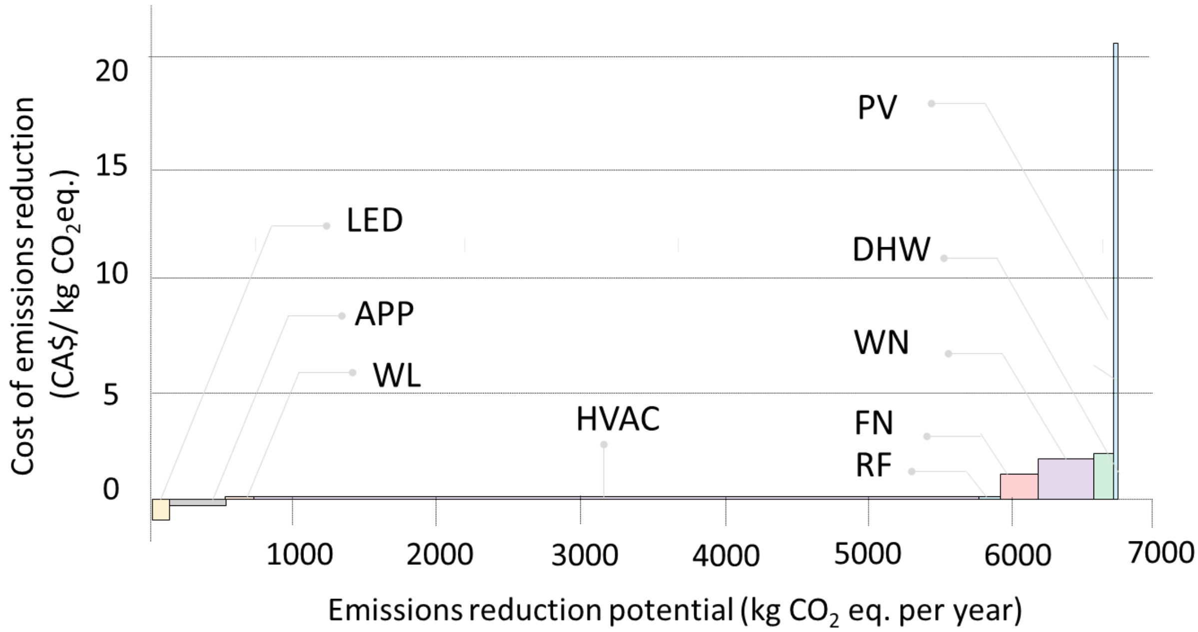
Payback period and carbon footprint: **Figure 4-6** shows the relationship between the extra initial expenditure and PBT and reduction in GHG for the 47 shortlisted energy upgrades. Three main clusters of energy upgrades associated with initial expenditure and PBT can be clearly identified from this figure. It was observed that for investments below CA$ 5,000, the PBT are all less than 15 years. This kind of investment may not only be suitable for most owner-occupants since the average tenure calculated for homeowners in North America is 8-years [324]. The cluster in the middle shows options of energy upgrades when the extra expenditure ranges between CA$ 8,600 to 1,200. It was observed that some of the energy upgrades that have the potential for decreasing GHG emissions beyond kgCO_2-eq have a high PBT of up to 30-years. The energy upgrades were also seen to offer more GHG reduction in combinations as compared to individual upgrade. For instance, the energy upgrade combination "RF WL LED HVAC DHW" provides about 200% more GHG reduction than PV systems for the Occupancy Profile 1. For the investment between CA$ 17,000 to 22,000, the majority of the energy combinations provide high reductions in GHG emissions. Since the budget required for these upgrades is high, financial help in the form of financial incentives from the government or utility providers would be needed to make these energy upgrades desirable for the users.

Marginal abatement cost curve: Marginal abatements curves are another effective tool to visualize the economic and carbon reduction potential of EPUs. One strength of these curves is the ability to also represent the negative costs associated with adopting some EPUs [325]. Each box on the abatement curve represents the consequences of adopting an EPUs combination. The data generated from EPUs evaluation for Occupancy Profile 1, relative life cycle costs and GHG reduction potential, is used to create a marginal abatement curve. The curve shown in **Figure 4-7** is generated for individual energy upgrades. A similar curve can be drawn for all 514 simulations performed. Likewise, abatement curves can be drawn for the 47 short listed EPUs used in **Figure -5**. The drawn curve shows that the HVAC system has the highest potential to reduce GHG emissions. In contrast, the incorporation of higher wall insulation will be a cheaper option for the residents. It is also observed that the costs of reducing GHG emissions are high for PV system. These high costs of PV are expected to decrease with time.



Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; PV: Photovoltaic panels; LED: Light emitting diode; RF: Roof insulation; WL: Wall insulation; FN: Insulated concrete form foundation

Figure 4-6 Occupancy Profile 1: Bubble chart with details of IC, PBT and GHG emission reduction associated with energy upgrades



Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; PV: Photovoltaic panels; LED: Light emitting diode; RF: Roof insulation; WL: Wall insulation; FN: Insulated concrete form foundation

Figure 4-7 Occupancy Profile 1: Marginal abatement cost curve

TOPSIS Results: In order to rank the energy upgrade for each profile decision matrix composed of initial cost investment, the payback period and GHG emissions were constructed. **Table 4-5** show the results of the first ten highest-ranked energy upgrades. It is seen that among the given scenarios, the choices for pro-economic scenario shows the highest variation in GHG emission reduction, IC and PBT. It is seen that as the decision-maker preference changes from pro-environment towards pro-economic, lesser energy upgrades are used. Roof insulation (RF), wall insulation (WL), lighting upgrade (LED) and upgrade of the domestic hot water system (DHW) are the only upgrades that were found in the list of top ten energy upgrades for the five user preferences. It is interesting to note that for a family of four, the DHW forms part of EPUs combinations under all scenarios. Water heating in Canadian homes accounts for 20% of the energy consumed and also accounts for a large portion of the residential carbon footprint [326]. A family of four is likely to spend more hot water in showering and bathing and hence are able to get more benefits by using a more efficient water heating system. An upgraded HVAC system forms part of the majority of the EPU combinations. The upgraded HVAC has a ground source heat pump and is known to bring

Table 4-5 Occupancy Profile 1: Ranking for energy upgrade for decision-maker preferences

Pro-Environment — User-defined — Pro-Economic

Ranking	Scenario-1	Scenario-2	Scenario-3	Scenario-4	Scenario-5
1	RF WL HVAC DHW PV	RF WL LED HVAC DHW	RF LED HVAC DHW	RF LED HVAC DHW	LED
2	RF WL LED HVAC DHW PV	RF WL LED HVAC DHW PV	RF WL LED HVAC DHW	LED HVAC DHW	RF LED
3	WL HVAC DHW PV	RF LED HVAC DHW	RF LED HVAC DHW PV	RF WL LED HVAC DHW	LED DHW
4	RF WL LED HVAC DHW	RF LED HVAC DHW PV	RF WL LED HVAC DHW PV	RF LED HVAC DHW PV	RF LED DHW
5	RF HVAC DHW PV	RF WL HVAC DHW PV	LED HVAC DHW	RF WL LED HVAC DHW PV	DHW
6	RF WL LED HVAC PV	RF HVAC DHW PV	WL LED HVAC DHW PV	LED HVAC DHW PV	RF DHW
7	WL LED HVAC DHW PV	WL LED HVAC DHW PV	LED HVAC DHW PV	WL LED HVAC DHW PV	WL LED DHW
8	RF LED HVAC DHW PV	WL HVAC DHW PV	RF HVAC DHW PV	RF HVAC DHW PV	RF WL LED DHW
9	HVAC DHW PV	RF WL LED HVAC PV	RF WL HVAC DHW PV	RF WL HVAC DHW PV	WL LED
10	RF LED HVAC DHW	HVAC DHW PV	HVAC DHW PV	RF LED HVAC PV	RF WL LED

Table 4-6 Occupancy Profile 2: Ranking for energy upgrade for decision-maker preferences

Pro-Environment — User-defined — Pro-Economic

Ranking	Scenario-1	Scenario-2	Scenario-3	Scenario-4	Scenario-5
1	RF WL LED HVAC DHW PV	RF LED HVAC DHW PV	RF LED HVAC DHW PV	RF LED HVAC DHW PV	LED
2	WL LED HVAC DHW PV	LED HVAC DHW PV	LED HVAC DHW PV	LED HVAC DHW PV	RF LED
3	RF LED HVAC DHW PV	RF WL LED HVAC DHW PV	RF WL LED HVAC DHW PV	RF WL LED HVAC DHW PV	LED DHW
4	LED HVAC DHW PV	WL LED HVAC DHW PV	WL LED HVAC DHW PV	WL LED HVAC DHW PV	RF LED DHW
5	RF WL WN LED DHW PV	LED	LED	LED	DHW
6	WL WN LED DHW PV	RF LED	RF LED	RF LED	RF DHW
7	RF WN LED DHW PV	LED DHW	LED DHW	LED DHW	WL LED DHW
8	WN LED DHW PV	RF LED DHW	RF LED DHW	RF LED DHW	WL LED
9	RF WL WN DHW PV	DHW	DHW	DHW	RF WL LED DHW
10	RF WL LED DHW PV	RF DHW	RF DHW	RF DHW	RF WL LED

Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; PV: Photovoltaic panels; LED: Light emitting diode; RF: Roof insulation; WL: Wall insulation; FN: Insulated concrete form foundation a number of technical, environmental and socio-economic benefits [327]; however, this system's initial investments are high and show a long payback period unless some external financial incentives are present. Hence, it is not surprising that this upgrade did not form part of the top ten pro-economic choices. Contrary to the HVAC upgrade, the LED is a very cost-effective EPU and forms part of a suitable energy upgrade choice. Solar photovoltaic (PV) system installation is another renewable option that was tested for case studies. Though the costs of PV system have decreased substantially over the past decade, PV was not part of scenario-5 choice. However, the electricity costs are rising; for instance, over the past decade, electricity rates in Ontario, Canada rose by 7.7% [328]. This implies that the use of PV upgrades may soon become a pro-economic in addition to a pro-environment choice. In addition, three energy upgrades that did not form part of top-ranked combinations in any of the five preference scenarios were windows (WN), ICF foundation wall (FN) and appliances (APP). All these options required large expenditure and the associated GHG reduction were not significant to form part of the top pro-environment related choices. Hence, for a typical family of four, the energy upgrades that need to be emphasized are DHW, HVAC, LED, PV, WL and RF.

4.4.2 Occupancy Profile 2

Occupancy Profile 2 comprised of a retired couple who spend most of their time at home.

Annual operational energy: **Figure 4-8** depicts the energy savings possible with respect to the selected upgrades for Occupancy Profile 2. Similar to energy savings groups made for occupancy, the selected EPUs were grouped into four categories based on their energy saving potential with respect to a base case annual energy 105.62 GJ/yr. It can be seen that the filtered EPUs for the retired couple give significantly more savings for similar EPUs than those for Occupancy Profile 1 EPUs. The majority of EPU give energy savings in the range of 21-39%. The highest savings of 71% are observed for the combination “WL LED HVAC DHW PV”. Similar to Occupancy Profile 1, WL and RF insulations yielded the highest savings among the passive systems and DHW gave savings among the active systems.

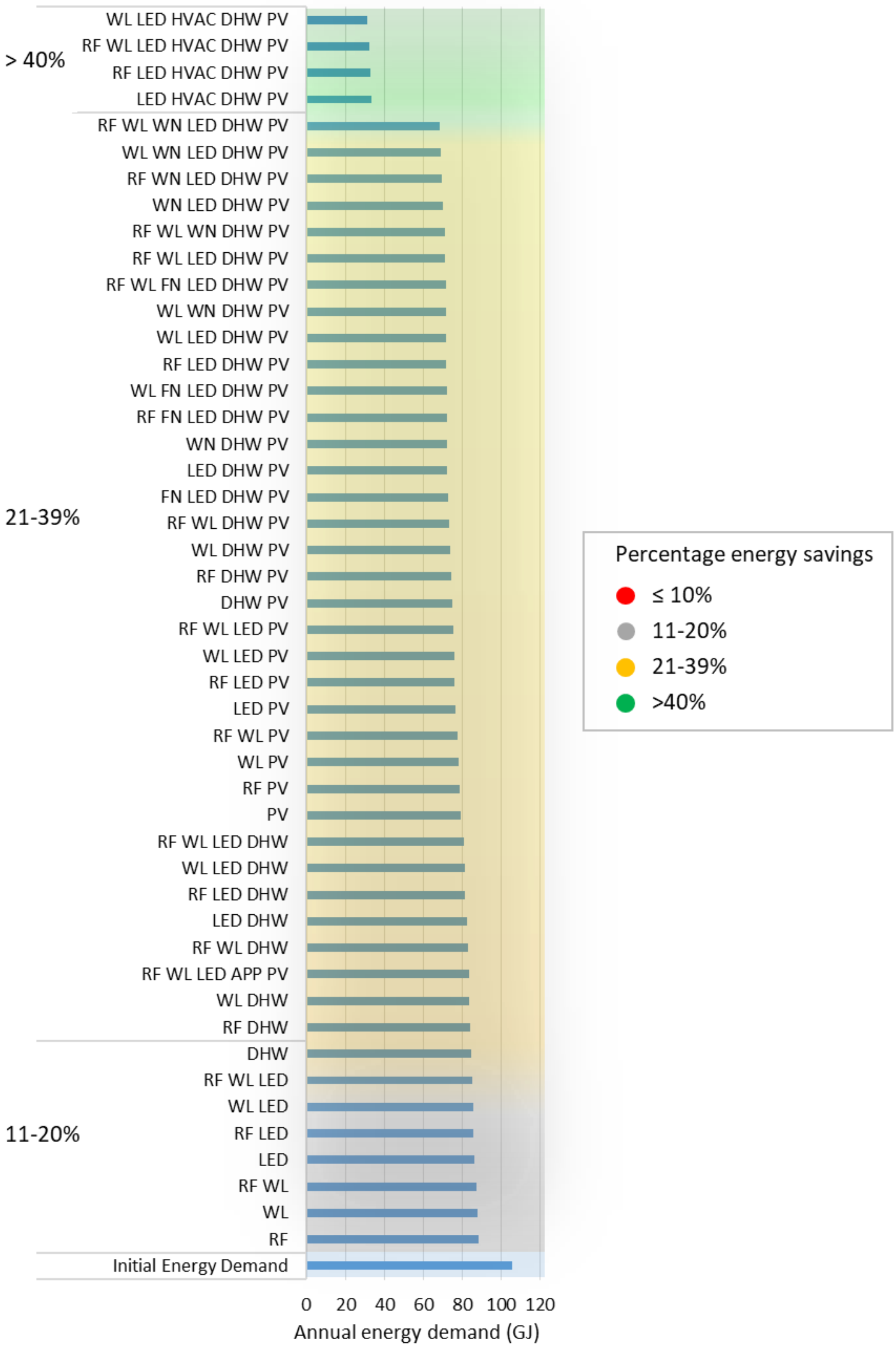
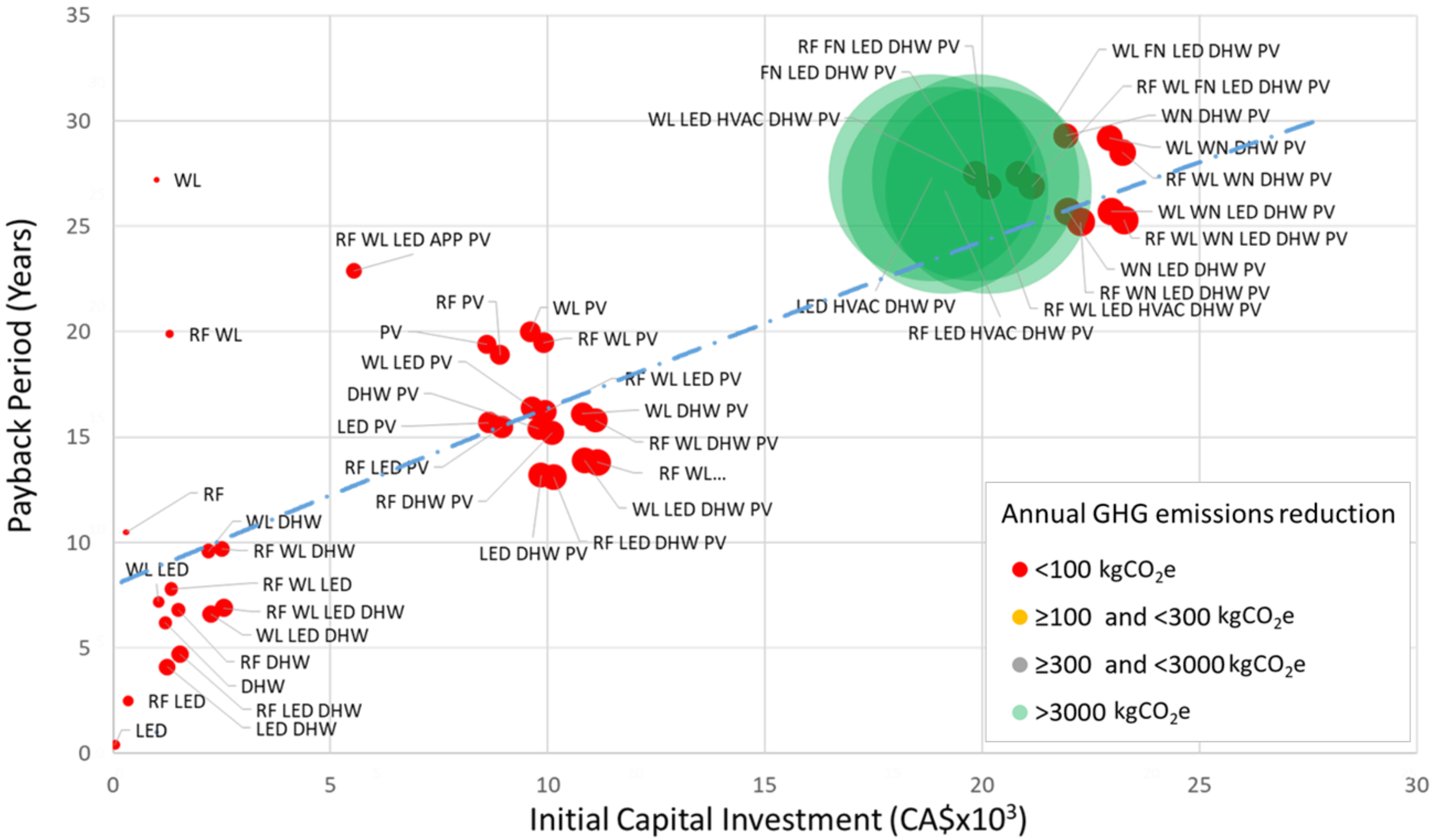


Figure 4-8 Occupancy Profile 2: Reduction in annual energy demand

Payback period and carbon footprint: Occupancy Profile 2 is depicted in energy use under different energy upgrades for the stay at home retired couple. The initial costs, PBT and GHG emissions for feasible energy upgrade options for Occupancy Profile 2 are shown in **Figure 4-9**. Similar to Occupancy Profile 1, energy upgrades can be seen as clusters between expenditure and PBT. However, a clear contrast between the two profiles is a very low GHG reduction (less than 100 $kgCO_2$-eq) associated with the majority of the upgrades. Hence, it is indicated that the energy use by Occupancy Profile 2 is significantly different from Occupancy Profile 1 and offers few options to reach the same level of GHG reduction targets. The highest reduction potential for Occupancy Profile 2 for the case study was found for the combination "RF WL LED HVAC DHW PV". It is observed that for this profile, a higher investment of up to CA$ 11,000 is not significantly decreasing GHG emissions. Therefore, for Occupancy Profile 2 in order to achieve high reduction targets needed to achieve sustainable buildings will require external help from the government and other organizations. This is also significant since the majority of the studies have shown senior residents often own bigger houses and usually have a low-income source [329].

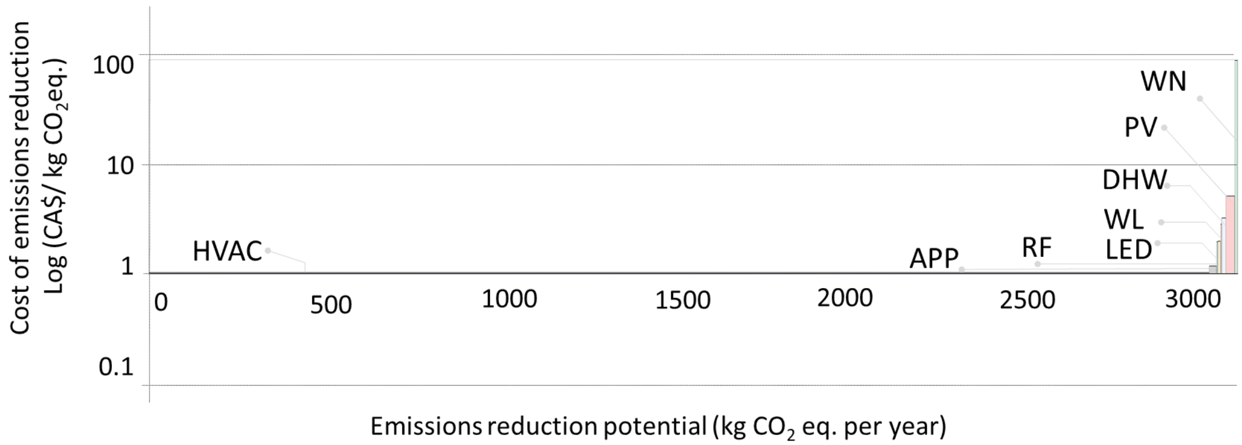
Marginal abatement cost curve: The data generated for Occupancy Profile 2 is used to create marginal abatement curve for individual energy upgrades (**Figure 4-10**). It is observed that the HVAC system has the highest potential to reduce GHG emissions, while the incorporation of more efficient windows is the most expensive option. Comparing the two abatement curves demonstrates that even the individual energy upgrades yield different performance according to the occupancy profile. It is also interesting to note that for Occupancy Profile 1 the LED and APP showed negative abatement curves while they are positive for Occupancy Profile 2. In addition, the change to ICF foundation does not provide notable emission reductions. These abatement curves need to be expanded to include EPUs combinations' performance and make more informed decisions.

TOPSIS results: As **Table 4-6** shows ranking for the top ten upgrade choices for the house with the retired couple defined by Occupancy Profile 2. Similar to the trends shown for Occupancy Profile 1,



Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; PV: Photovoltaic panels; LED: Light emitting diode; RF: Roof insulation; WL: Wall insulation; FN: Insulated concrete form foundation

Figure 4-9 Occupancy Profile 2 (b) Bubble chart with details of IC, PBT and GHG emission reduction associated with energy upgrades



Note- HVAC: Heating, Ventilation, and Air Conditioning; DHW: Domestic hot water; HRV: Heat recovery ventilation; PV: Photovoltaic panels; LED: Light emitting diode; RF: Roof insulation; WL: Wall insulation; FN: Insulated concrete form foundation

Figure 4-10 Occupancy Profile 2: Marginal abatement cost curve

more energy upgrades are needed for a greater reduction in GHG emissions. It is seen that single EPUs form part of the highest ranked EPUs for Occupancy Profile 2. These finding is in line with the results shown by abatement curve in **Figure 4-10**. For instance, WN upgrades does not form part for any top ten EPUs combinations. The main reason for this is the higher cost required to achieve per unit of GHG reduction.

These findings imply that a larger expenditure is needed for achieving meaningful GHG reduction. Some studies have also shown that the older occupants belong to the low-income group. This implies that increased energy use accompanied by higher initial investment and longer PBT needs to be addressed by utilities and the government. Some utilities in Canada are already offering incentives for increasing the energy efficiency of homes occupied by senior citizens. However, more extensive and tailored incentives for this age group are still needed.

4.5 Discussion

The above results demonstrate the suitability of different EPUs with respect to occupancy profile and investor’s priority. It is observed that low-cost energy upgrades have a higher potential for energy savings for Occupancy Profile 2. However, combinations of high-cost EPUs provide greater energy saving and GHG emission reduction potential for Occupancy Profile 1 as compared to Occupancy Profile 2. This finding validates simulated results found by Motuziene and Vilutiene

[271], who observed higher savings for houses with four occupants compared to working and retired couple profiles. This higher energy savings for Occupancy Profile 1 can be attributed to a higher number of occupants. De Meester et al. [330] work on different occupancy profiles also showed that as a house becomes more efficient, occupants' internal heat gains play an important role in decreasing heating energy demand. Higher savings are observed for Occupancy Profile 1 since space heating is still the predominant end-use energy (64%) in residential buildings of Canada [331].

4.5.1 Investor Preference

This study did not find a significant difference between the energy upgrade for the pro-economic preference for the two profiles. However, changes in both ranking order and the type and number of energy upgrades vary with the pro-environment preference. This finding has important implications for developing tailored energy audit and energy saving incentives programs. Currently, energy audit and energy saving incentives programs by government and utility providers are designed on the basis that decisions related to EPU selections are based on the most cost-effective measure [332]. Since a visible difference is present between the ranking of energy upgrades from pro-environment to pro-economic, there is a need to consider factors influencing the investors' decisions. Future research should collect the investor’s preferences through a questionnaire survey. This will help both the home dwellers assess the most feasible energy upgrades according to their criteria and the policymakers for designing effective energy policies.

4.5.2 Occupancy Profile

The results from this case study are important, as they are representative of energy use based on actual occupancy profiles. The differences in the EPUs ranked for the two profiles show there is a need to incorporate the type of occupancy and the preference of owner-investors in selecting EPU. Occupancy Profile 2 represented retired couple (aged between 50 and 64) that accounted for about 21% of Canada’s national population [333]. It is predicted that this age group will keep increasing, usually accompanied by smaller household sizes (single or couples). Furthermore, the occupancy patterns of the retired couple are similar for demographic groups such as people working from home, jobless, or homebound due to disability [334]. Hence, it is imperative that future energy policies and incentives for energy efficient buildings are designed accordingly. The study results can be applied to other countries having similar occupancy behaviors as Canada, such as the US and UK [335]. The methodology can be applied in other countries of the world through the update of local weather conditions, local terrain, types of home dwellers and socio-economic conditions. The findings of this study are restricted to two occupancy profiles that represent only 52.3% of the Canadian private households. According to Statistics Canada [307], private households are divided into 7 occupancy profiles:(1) Couples with children (Occupancy Profile 1 for this study) (26.5%), (2) Couples without children (Occupancy Profile 2 for this study) (25.8%), (3) Lone parents (8.9%) (4) Multi-generational households (2.9%), (5) One-person households (28.2%), (6) Households with two or more persons (4.1%) and (7) Other households. Therefore, caution is recommended when applying the results of this study to houses with different occupancy profiles. The type of occupancy profile will affect the amount of energy savings associated with EPUs as well as the priority of stakeholders related to investment in energy upgrades. For example, Poortinga et al. [336] showed that single and senior occupants have a low willingness to invest in energy savings. Similarly, high–income residents consume more energy than low-income earners but are also willing to pay more for energy investments [336,337].

Likewise, the occupancy patterns can change over time and will affect the selection of EPUs. For example, the COVID-19 pandemic has increased occupancy period at home [338]. As a result of this pandemic, homes have been transformed into mixed-use spaces where home-schooling, office work, recreational activities and social interaction have become norms. Similarly, the percentage of remote or home workers had been steadily increasing in Canada and other countries of the world, even in pre-pandemic conditions [339,340]. EPUs selection should consider these emerging dynamics.

4.5.3 Financial Incentives

Financial incentives in the form rebates, subsidies, grants are offered to promote the residential building energy upgrades and form a major part of energy policies [18,25]. These incentives reduce financial risks for investors and help in meeting carbon mitigation goals. A number of financial incentives are also present in British Columbia and other regions of Canada through government and private organizations [341]. The largest financial incentives are present in the form of rebates offered by local utility providers. Currently, these rebate incentives are available for various household appliances, water heater, heating equipment and insulation [342]. These incentives were not considered in the life cycle cost analysis, as incentives are subject to change over time as new energy policies and building energy codes are implemented. The inclusion of these and other government incentives (for a specific time period) will reduce the LCC and change the ranking of the EPUs options for the two occupancy profiles.

4.5.4 Other Factors Impacting EPUs Ranking

In addition to the occupancy profile, other factors can also influence the selection of optimal energy upgrades. Financial incentives were not considered, as the study aimed to analyse the impact of OB alone. When FIs are considered, the LCC will be reduced and rankings of EPUs will change. Similarly, the carbon footprint of the energy mix in British Columbia is very low compared to the other regions of Canada [343]. Therefore, the GHG emission reduction potential for energy upgrades will be higher for regions with energy generation based on fossil fuels. Another factor affecting the ranking of energy upgrades will be the typology of the house. The energy consumption and the expenditure involved in the installation of the energy upgrades will vary with the type (detached, semi-detached and terraced) of the residence [329]. In the current study, single-family detached homes of medium size were considered for methodology demonstration. Bastos et al. [344] study indicate the energy demand and carbon emissions per covered area from large houses is less compared to smaller residences. Compared to large single-family detached homes, multi-unit residential buildings have higher operational energy requirement per unit area. Furthermore, the operation and maintenance cost of apartments are high [345]. A commonly observed split-incentive problem may also impact the selection of EPUs for multi-unit residential buildings due to uneven cost and benefits distribution between the building owners and renters [346]. Considering the impact of these factors it is suggested the influence of these factors is not ignored for the selection and ranking of EPUs.

4.5.5 Validation of TOPSIS method

TOPSIS method was used to rank energy performance upgrades for the two occupancy profiles. TOPSIS method was selected due to its and ability to rank alternatives based on the shortest distance from the ideal. This method has been successfully used on energy performance upgrade selection in literature [300–303]. However, rank reversal is a common problem associated with

TOPSIS [347] and the performance of any MCDM method varies with application [348]. Therefore, it is essential to verify ranking results obtained for the tested EPUs and occupancy. This research did not validate the results obtained from the TOPSIS method. Future researchers can validate these results by comparing these results with ranking obtained from at least three other MCDM techniques [349,350]. Compared to TOPSIS, a different MCDM method (AHP, PROMETHEE, ELECTRE) may provide a different ranking. Comparing ranking results from three MCDM methods will verify the findings obtained from TOPSIS.

4.6 Summary

This chapter provided a two-step methodology that is able to assess the effect of occupancy profile on the selection of the most suitable EPUs in new residential buildings. In particular, this chapter (1) developed calibrated models using one-year monitored data for predicting energy use associated with individual occupancy profile; (2) applied the calibrated model to holistically evaluate energy upgrade options and lastly (3) enabled prioritization of different upgrades through the application of TOPSIS with a variable weighting scale to enable flexibility in defining user preferences. The proposed methodology was demonstrated through comparison in EPUs required for the two most common occupancy profiles in Canada: a family of two working adults and dependent teenagers and a stay at home retired couple. The results showed that a single-family detached house family of four is capable of reducing GHG emissions at a higher rate as compared to the application of the same upgrades in the house of a retired couple. The preferences based weighting showed that when pro-economic is the sole criterion, the choices of applicable EPUs are limited and similar for different occupancy profiles, but when decision-makers move towards a pro-environmental behavior their choice will change both the ranking and EPUs options. The new understandings from this study can be used for community-level residential building planning. This unique methodology can assist developers, planners, potential owners and practitioners in developing single-family detached houses for retired communities, typical urban communities in Canada and other developed countries.

Chapter 5 Effectiveness of Financial Incentive Policy for Meeting Building Energy Code Requirements

Parts of this chapter will be submitted in the Elsevier journal *Energy*, as an article titled "Financial Incentives for new residential buildings in Canada: Investigating effectiveness using sensitivity analysis" [263].

5.1 Background

Greenhouse gas (GHG) emissions related to energy are a significant cause of the climate emergency. The building sector accounts for up to 39% of the energy-related GHG emissions. The residential building sector, in particular, is responsible for up to 25% of the total energy consumption and 17% of GHG emission [351,352]. The construction of energy efficient residential buildings can play a crucial role in addressing increasing energy demands, depleting resources and causing negative environmental impacts [353,354]. Moreover, energy efficient residential buildings are associated with economic savings, improved thermal comfort and better indoor air quality leading to improved health and well-being of occupants [108,355–358]. Building energy codes (BEC), standards and regulations are common policy instruments used to increase the ratio of the energy efficient residential building stock and obtain the above-mentioned benefits. In order to combat environmental issues, there has been a pragmatic shift towards the implementation of more stringent sets of BEC and standards as part of regional, national and international energy policies over the recent years. [359].

BEC as regularity policy instruments mandate energy performance targets to be obtained by a building and are usually enforced by regional and provincial governments, such as the British Columbia Energy Step Code (BC-ESC) and California Title 24 [306,360,361]. Building standards, on the other hand, provide guidelines for energy efficient buildings and are not mandatory. These are typically provided by a national organization, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards [361]. In North America, net-zero energy building (NZEB) codes are the most popular due to the potential benefits at individual building and community levels [362–364]. Some BEC aim NZEB such as BC-ESC, California Title 24 and NYStretch Energy Code-2020 [306,360,365]. Despite the benefits associated with advanced BEC, their implementation is often delayed due to obstacles that either delay or hinder widespread implementation. Among these, the most common and frequently cited obstacle is the large cost premium needed to construct such buildings. For instance, Yip and Richman [366] performed economic analysis for a new residential home in Ontario, Canada. It was found that a premium of up to 51,564 US$ is required to reduce heating energy 80% below the existing BEC. Similarly, Barkokebas et al. [288] performed a life cycle cost analysis over a 30-year period for a new residential home in Alberta, Canada. It was revealed that the operational energy savings did not cover the initial investment and required an additional amount of at least 66,640 US$. Thus, high economic risks are associated with the implementation of stringent BEC.

Financial Incentives (FIs) are policy instruments most often provided by the government and utilities to make the implementation of BEC economically viable [216]. FIs are able to change the consumer's behavior and investment convenience either by rewarding (e.g. grants, subsidy, tax-credits) or through penalizing (e.g. carbon tax)[21]. Similarly, the role of FIs is well recognized in widespread applications of renewable energy sources and technologies [23,24]. The synergy between BEC and FIs is well established in the literature and these two policy instruments have been proven to positively reinforce each other in achieving desired targets [249]. Despite the importance of FIs in achieving energy efficiency targets, there is limited research in this area. The majority of studies have dealt with BEC compliance and FIs impacts separately. Recent studies on FIs evaluation are mostly restricted to single energy upgrades, such as solar photovoltaic system and heat pumps [52,54,367]. Furthermore, most studies have predominantly focused either on commercial buildings or on one residential archetype (i.e. single-family detached home) [54,368–370]. The impact of FIs is subject to uncertainties related to building design, occupancy and the local economic conditions, although a limited number of studies have incorporated these factors for assessing FIs [21,40]. In order to provide a comprehensive decision direction for improving FIs designed for emerging BEC, the environmental and economic impacts should be quantifiable and easily understandable. Hence, there is an urgent need for a methodology that can provide a comprehensive evaluation of FIs and accurately provide the economic and environmental benefits associated with BEC adoption.

"Effectiveness" is one of the most fundamental criteria that can quantitatively measure the outcomes and benefits of FIs [18,21]. The effectiveness of FIs has been defined in a number of domains and perspectives, ranging from the effectiveness of FIs from government perspective (e.g.

degree of energy efficient technologies penetration) to end users' perspectives (e.g. energy savings possible with the use of FIs) [52,75,78,369–373]. Similarly, FIs effectiveness will vary according to the intended goal of the study and is most commonly expressed in terms of cost and/or environmental effectiveness [21]. Environmental performance indices have been successfully used in literature to aggregate economic and environmental parameters/indicators and evaluate the policy [199,374–376]. Such indices are able to represent complex information in an easily comprehensible form [377]. Hence, aggregation of economic and environmental indicators as a single index can be used to comprehensively assess the impacts of FIs related to BEC.

This chapter endeavors to fulfill the above-mentioned gaps through the introduction of a FIs evaluation methodology from end-users' perspectives. Here, end users are defined as the developers and building owners who will make decisions regarding the investment in energy upgrades of the residential buildings. Specifically, this methodology will help understand the relationship between FIs and related energy, cost and GHG reduction among residential archetypes. A large number of FIs are provided in the form of rebates. Therefore, this research considers a case study of rebates offered for meeting new BEC targets. From this part onwards, the terms financial incentives, FIs and rebates will be used interchangeably. The proposed methodology will measure effectiveness from the end-users' perspective. The specific objectives of this research are:

(1) Develop a methodology for effectiveness evaluation of FIs related to BEC.
(2) Assess the FIs effectiveness sensitivity under key design and economic parameters of residential archetypes.

The original contributions of the study are as follows:

(1) A multi-stage methodology that utilizes a rule-based screening method to identify the most appropriate energy efficiency measures and applicable FIs for meeting BEC requirements.
(2) Introduces a "FIs effectiveness index" that can be a useful tool for decision-makers to visualize cost and environmental implications of FIs.
(3) Uses rebates offered on an advanced BEC called stretch code that is being adopted in different regions of North America.

(4) Demonstrates the proposed methodology by application on FIs related to BC-ESC considering seven residential archetypes (that represent 90% of archetypes in British Columbia's residential sector) and three climatic locations.

5.2 Methodology

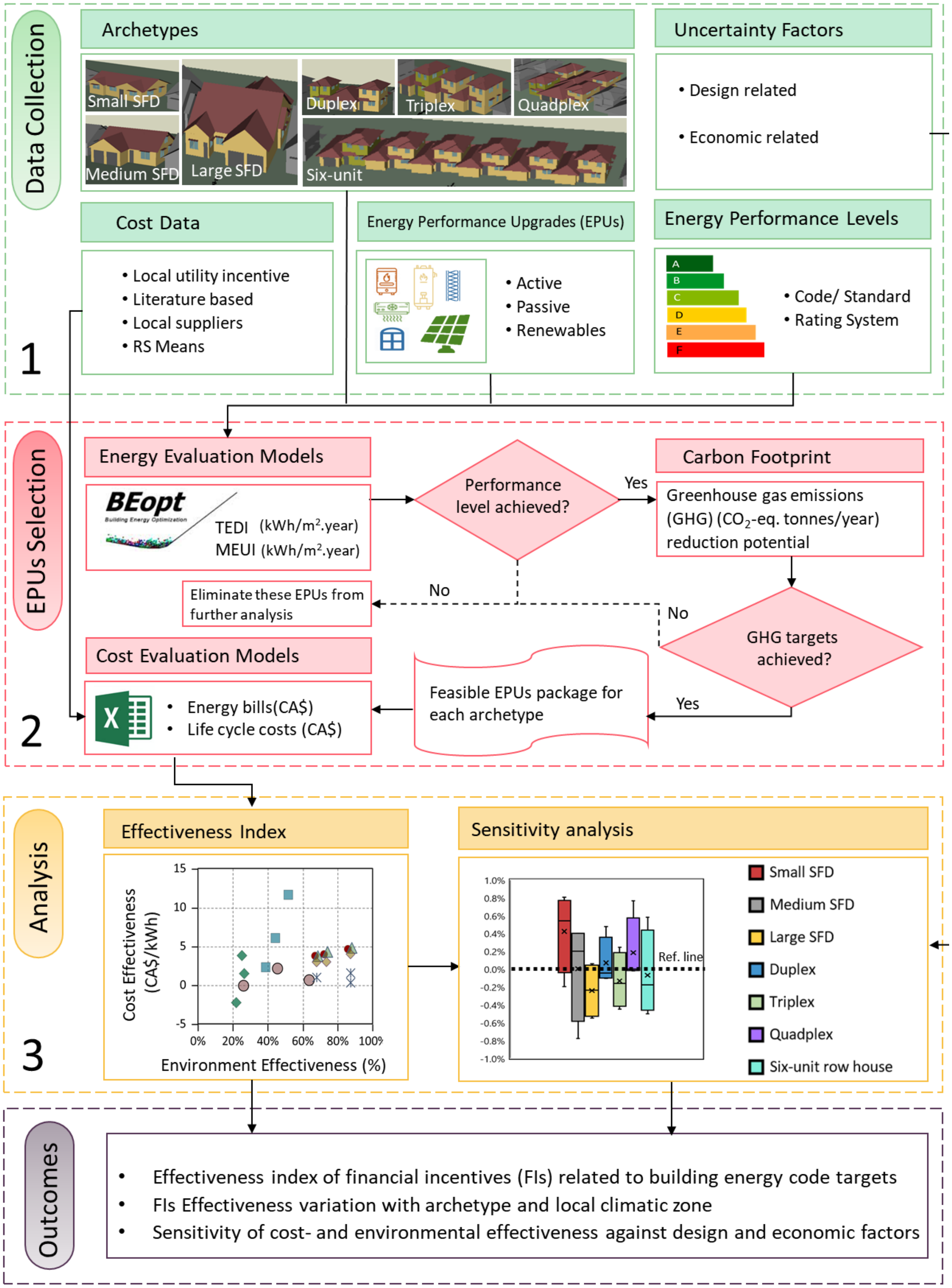
The specific aim of this research is to assess the effectiveness of FIs offered for residential buildings to meet performance-based targets. To meet the research objectives, a multi-stage research methodology is introduced (**Figure 5-1**). The stages include (1) data collection, (2) determination of applicable rebate and (3) evaluation of FIs effectiveness index and its sensitivity analysis. The methodology is illustrated through a case study of FIs in the form of rebates available for a new BEC in British Columbia, Canada, called BC-ESC [177]. The BC-ESC was chosen because it is considered to be the blueprint for future upgrades in the national building energy code of Canada [378].

5.2.1 Stage I: Data Collection

The first stage involved the data collection related to building archetypes, BEC, FIs, occupancy profiles, energy upgrades, cost data and energy carbon emission factors. Design and economic factors that may impact effectiveness were also identified. The primary sources utilized for data collection included peer-reviewed journal articles, local and international databases, local building energy regulations and policies and technical reports.

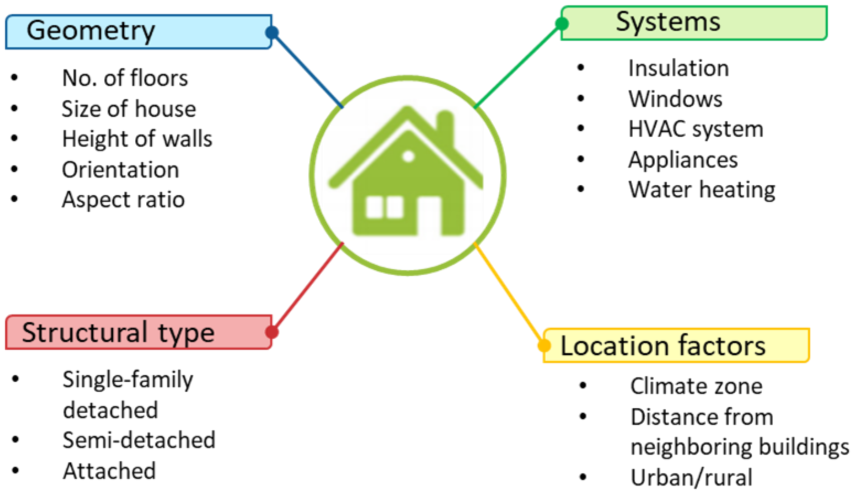
Building Archetype: The terms "building typology" or "archetype" refers to the categorization of buildings according to their function [288]. Archetypes aim to distribute building stock into homogenous groups in order to reduce computation time and determine the optimal solution. Criteria used for classification of archetypes involved (1) building geometry; (2) energy systems; (3) structural type; and (4) location (**Figure 5-2**).

Energy performance level: BEC with fixed targets (such as stretch codes) gaining popularity since they provide a higher degree of certainty and a time to revise BEC to attain energy policy targets. These codes also help bring innovation and provide time for a smooth transition for the industry [379]. Many regions in North America have started to adopt or plan to adopt BEC with fixed targets; therefore, the energy performance levels set by these codes were considered for this research. **Table 5-1** provides metrics used in the methodology for FIs evaluation.



Note- TEDI: Thermal Energy Demand Intensity; MEUI: Mechanical Energy Use intensity; SFD: Single family detached home

Figure 5-1 Research methodology



Note- HVAC: Heating, Ventilation, and Air Conditioning

Figure 5-2 Criteria considered for defining residential building archetypes (*Source*: [288,380,381])

Table 5-1 Common metrics used of energy performance levels

Metrics	Metric (Abbreviation) Units	Formula	Ref.
Energy	Thermal Energy Demand Intensity (TEDI) kWh/m^2/yr TEDI measures the amount of energy required to have comfortable indoor temperatures	$TEDI = \frac{Space\ and\ Ventilation\ Heating\ Output}{Modelled\ Floor\ Area}$	[382]
	Mechanical Energy Use intensity (MEUI) kWh/m^2/yr MEUI measures the total energy required for heating, cooling, ventilation and water heating systems. Lighting, plug loads and consumer appliances are not part of typically MEUI indicator	$MEUI = \frac{Total\ Annual\ Energy\ Consumption - Ba}{Modelled\ Floor\ Area}$	[382]
Environment	Greenhouse Gas Intensity (GHGI) kg.CO_2/m^2 Where, GHGI is greenhouse gas intensity and dependent on the energy used on-site, using emission factors of different energy sources used	$GHGI = \frac{Site\ Energy\ Use\ x\ Emission\ Factor}{Modelled\ Floor\ Area}$	[383]

Energy performance upgrades: Energy performance upgrades (EPUs) are alternative materials, equipment or appliances that improve building energy performance to achieve BEC. EPUs for a building are typically divided into three categories: passive, active and renewable EPUs [263,384,385]. Locally available technologies were used in the methodology to predict the impact of rebates.

Financial Incentives and other cost data: Incentives are provided for energy investment and are generally in the form of rebates for achieving BEC requirements. The amount offered is independent of the energy saving actually achieved, provided the minimum requisites are fulfilled, so that the economic efficiency of the intervention and, most importantly, the action on the entire building stock is left to the owners' decision [28]. Investment-related cost data were collected through quotations from local suppliers, online market rates of materials and/or from established and verified databases such as RSMeans [386]. Local utility rates were used for evaluating operational energy costs, while the replacement and maintenance rates were obtained from expert opinion or values used in literature. Similarly, discount and utility escalation rates were adopted based on local historical data.

Uncertainty factors: A number of uncertainties related to engineering design and economic parameters can affect the ultimate decisions. Building heating and cooling loads are especially impacted by the local climatic conditions [387]. Similarly, design factors such as window-to-wall ratios (WWR), building aspect–ratio, orientation, distance from neighboring buildings or trees and number of floors in a building are considered as uncertain parameters in existing literature [388–390]. These design parameters will ultimately impact the energy costs of a house. Uncertain economic parameters most commonly considered are discount rates, fuel escalation rates, mortgage and interest rates and digression cost of technology [47,391,392]. These factors were obtained from the literature and technical reports.

5.2.2 Stage II: Identification of Feasible Energy Performance Upgrades

A stepwise rule-based screening methodology was used to determine the feasible energy upgrades required to achieve BEC. The method consisted of energy model development, calculation of energy performance metrics, determination of applicable FIs and evaluation of cost and GHG emission. The screening was performed from the end users' perspective. These steps are explained as follows.

Energy modelling: Energy performance can be evaluated either through a forward or inverse approach [393]. The forward approach, also called the classical approach, is most common and utilizes information on building characteristics to construct energy models and assess the energy performance level achieved. Most common energy analysis software, such as EnergyPlus, DOE-2 and TRNSYS, utilize the forward approach. In contrast, the inverse approach, also known as the data-driven approach, is used when actual energy performance, weather, temperature and/or humidity data are available. The approach is used to construct a new or calibrate an existing model [394,395].

The proposed methodology utilized the forward approach to construct energy models for new residential buildings. Building Energy Optimization Tool (BEopt) version 2.8 was used to determine the energy performance of shortlisted archetypes. BEopt is a graphical user interphase (GUI) focusing on residential buildings in North America and uses EnergyPlus as a simulation engine [396,397]. BEopt provides good modeling capability of house plans though its 3D modelling capacity is limited [398]. The occupancy profiles are based on the number of bedrooms assigned to the model. The energy models constructed in BEopt were used to determine annual energy consumption by keeping intervals of one minute. A parametric analysis study was performed to evaluate the impact of individual and combined EPUs.

Heating and cooling loads determined from BEopt were used to estimate the energy performance metrics. The metrics values were compared with the BEC energy performance metrics. EPUs with values equal to or above desired targets were shortlisted while the remaining were discarded from further analysis. The short listed EPUs were used evaluating GHG emission reduction compared with base case values.

Selection of rebates: The quantity of rebates applicable varies with region and local bylaws. The maximum TEDI and MEUI levels achieved by EPUs was used to determine corresponding rebates. These values can be obtained from utility providers, local municipality, provincial and federal databases [21]. These rebates can be in the form of lump-sum amounts or can be grouped with additional incentives available for special EPUs (such as ground source heat pump or installment of solar photovoltaic systems) and additional rebates from the local municipality. The rebates associated with BEC level were used in cost analysis. It should be noted that for attached homes, the rebates were calculated with respect to each unit; therefore, the rebate for a single unit was multiplied with a number of units in an attached home to determine total rebates.

Cost Modelling: Cost modeling was conducted to further shortlist and refine the applicable EPUs. Cost modelling results are often determined as internal rate of return, benefit to cost ratio, life cycle cost assessment (LCC), profitability index and simple or discounted payback period [96,399]. Among these economic indicators, LCC determines a product or process's costs for an entire life span [285]. Usually, LCC for buildings includes costs from the construction to final demolition and disposal stages [286,287]. Recent studies on energy evaluation of new residential buildings in Canada have used relative LCC and a timeline of 30-year [263,288,289]. Relative LCC is based on the model provided by the US Federal Energy Management Program [290]. Compared to conventional LCC analysis, this model does not require extensive and time-intensive data collection. Relative LCC only requires costs associated with energy-related components before and after EPUs [291,292]. For current work, these costs included investments and operation-related costs (i.e. operational energy bills, maintenance and replacement of energy components), while the end of life cycle costs considered negligible. Hence, this research also adopted relative LCC as an economic metric, evaluated through the Net Present Value method [290] and a 30 year operation period. **Table 5-2** shows the cost metrics and their description used in this study. The last two metrics in this table: future energy costs and carbon tax rates, were utilized for conducting sensitivity analysis.

Table 5-2 Cost metrics

No.	Metric	Units	Model	Ref.
1.	Difference in total Life Cycle Costs ($dLCC_t$)	CA ($)	$dLCC_t = dC_c + dC_U + dC_{EOL}$	[263,384]
2.	Present value of future energy costs (P) under different fuel price escalation and discount rate	CA ($)	$P = A_0 * (\frac{1+e}{d-e}) \left[1 - \left(\frac{1+e}{1+d}\right)^N\right]$	[400]
3.	Carbon tax on natural gas	(CA$/tonnes CO_2e)	$Carbon\ tax = tax\ rate\ x\ EF_f$	[323]

Selection of EPU: The EPUs were selected based on GHG reduction potential and associated LCC. GHG emission reduction potential was assessed from the GHGI metric defined in **Table 5-1**. Most studies on code compliance follow the least cost approach as seen in recent studies in Alberta and Ontario [288,366]. However, EPUs with the least cost are not always environmentally efficient. In fact, EPUs selected by this method serve as low-hanging fruits that can lead to a lockdown effect that would restrict further energy efficiency improvements. Therefore, to obtain maximum benefit, both for the end-users and society, EPUs with the highest GHG reduction selected. The costs were determined for the EPUs selected from the second screening.

5.2.3 Stage III(A): Effectiveness Index

Cost (C_{eff}) and environmental (En_{eff}) effectiveness of FIs were evaluated from the end users' perspective. End users for this study refer to the developers or building owners who are major decision-makers in BEC implementation. An effectiveness index matrix was constructed that visually represented the impacts of FIs (**Figure 5-3**). C_{eff} metrics were adopted from Boza-Kiss [372] work on societal cost-effectiveness and helped identify the amount spent per energy savings. In this matrix, a negative value of C_{eff} shows that applied incentives are highly-cost effective and able to provide monetary savings for the end-users and vice versa. En_{eff} was defined as the GHG reduction potential and was expressed as the percentage change from the base case. Positive En_{eff} indicates a reduction in GHG emissions, while its negative value showed that GHG emissions had increased.

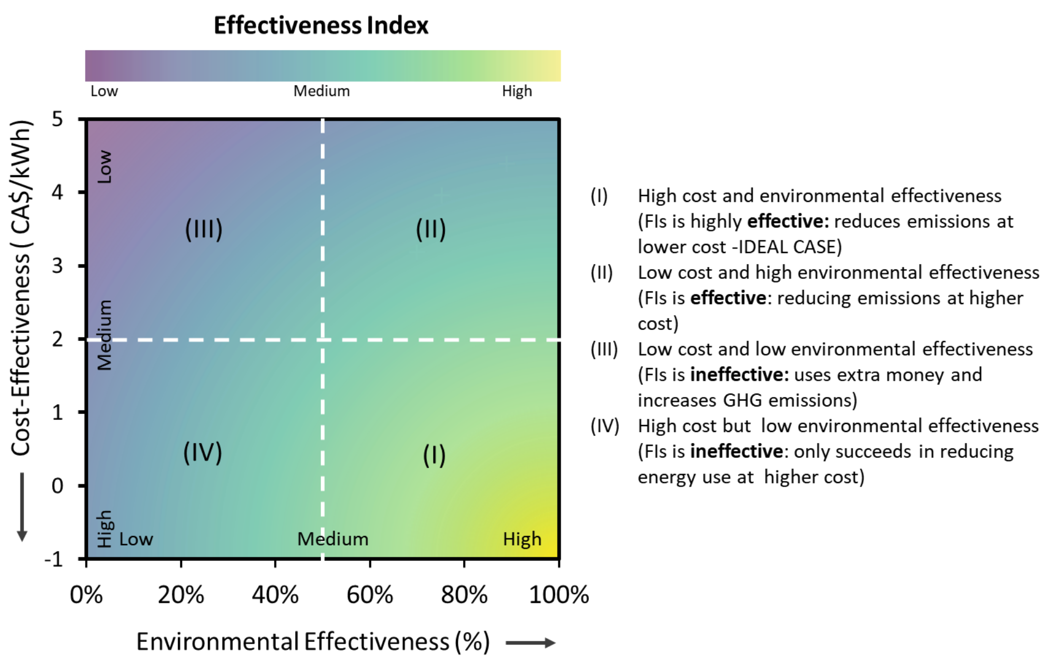


Figure 5-3 Effectiveness Index Matrix

Table 5-3 Effectiveness metrics

Effectiveness	Description	Unit	Ref.
Cost	$\frac{Cost\ of\ investment - Energy\ cost\ savings}{Energy\ savings}$	CA$/ kWh	[372]
Environment	$\frac{GHG\ emissons\ of\ base\ case - GHG\ emission\ with\ code\ complaince}{GHG\ emissons\ of\ base\ case}$	%	[75,197,217, 228,238]

5.2.4 *Stage III (B): Sensitivity Analysis*

Sensitivity analysis can help improve the efficiency of the design process and extract useful information for improvement and application for a larger audience [401,402]. To assess the impact of different uncertain parameters on C_{eff} and En_{eff} of available rebates, a local sensitivity analysis was used. Local sensitivity analysis uses a one-parameter-at-a-time (OAT) approach [387]. Here, one parameter is changed at a time keeping other factors constant [401,403]. The parameter values selected for sensitivity analysis are based on average values under normal conditions and tested against extreme possibilities. For instance, cost parameters such as interest, discount rates and fuel escalation prices should be based on most recent reports and databases [384]. In this methodology, uncertain parameters related to design and economic factors and based on previous studies were considered (**Table 5-4**). Design factors affected both C_{eff} and En_{eff}, since they impact energy usage and associated costs, while economic factors only affected the C_{eff}.

5.3 Methodology Demonstration

Canada's residential building sector has high energy use intensity values due to high space heating further augmented in the past few decades with rising space cooling demands [404]. To meet mitigation targets, the Pan-Canadian Framework on Clean Growth and Climate Change mandated provincial governments to develop advanced and innovative BEC codes for buildings. Step-codes (also called stretch codes) help ensure a smooth transition to net-zero energy pathways [405]. In the same vein, BC’s provincial government introduced the BC energy step code (BC-ESC) in April 2017 [69]. Currently, BC-ESC is a voluntary standard for new residential and commercial buildings that aims to move the construction to a net-zero status beyond the base case BEC of 2012. It establishes measurable TEDI and MEUI targets according to the building archetype and

Table 5-4 Details of the sensitivity analysis

Factors	Parameter(s)	Investigated values	Justification	Ref.
Design	Window-to-wall ratios (WWR)	4 ratios 10%; 12%; 15%; 18%	WWR are the area of openings relative to the building envelope. Windows are responsible for large portion of heat gains and losses; therefore, they directly impact heat balance and resultant energy usage.	[406,407]
	Orientation	8 Orientations N; NE; E; SE; S: SW; W; NW	Orientation is important design parameter and forms part of a number of sensitivity studies. It is important with respect to solar radiation; lighting and ventilation of building. 8 orientations representing a 45 degree interval rotation of each archetype	[406]
	Neighboring buildings	4 neighbor distances None; Left/right 10 ft; Left/right 15 ft; Left/right 20 ft	The neighboring buildings can act as shading to adjacent buildings. The distance to adjacent building varies with density of the neighborhood. The impacts may not be significant for individual buildings but would become significant at building stock scale.	[406]
Economic	Fuel Price (%)	3 price escalation: Low; Medium and High Electricity (2%; 6%;10%) Natural gas (2%; 5%; 8%)	The three fuel escalation rates low; medium and high are considered from Canadian context. The escalation rates are based on Energy Escalation Rate Calculator and data by National Energy Board of Canada.	[384,405,408]
	Carbon Tax Rate (CA$/tonne CO_2e)	4 carbon tax -Current Carbon tax rate[a] (40) -Carbon tax rate 2021(50) -Double Carbon tax rate 2021 (100) -Equal to Sweden tax rate (183)	A carbon tax is a form of disincentives that push the market towards energy efficiency and conservation. Commodities with high GHG emissions are assigned higher tax value and additional cash flow under abated carbon policy is achieved. Carbon taxes have been applied to fossil fuel commodities in British Columbia since 2008. These taxes are increasing every year and are projected to be 50 CA$ in 2021. Sweden has the highest carbon tax in the world and its consider an extreme case that can be adopted to curtain carbon emissions and consequent impact on cost-effectiveness of existing rebates.	[216,402,409,410]

(Note: due to the COVID-19 situation, the increase in carbon tax for 2020 had been postponed (*Source:* [411]). N: North; E; East; S: South; W:West location. These energy metrics are defined in **Table 5-1**. This research is limited to the application of this code on new residential buildings, since their rate of construction, is high in BC; for instance, construction of new residential buildings exceeded 81,000 in the year 2018 alone [412]. Hence, making new residential buildings complaint to BC-ESC will curtail the energy demands and the associated GHG emissions.

Among the various incentives present in BC, rebates from local utility providers are the most extensive in number [21]. In addition to the rebates offered for BC-ESC specifically [413] (**Figure 5-4**), other incentives and rebates are available that can be coupled with these rebates. The additional financial sources include rebates for special EPUs (such as air-source heat pump and energy star appliances), individual municipalities (to accelerate the rate of adoption of BC-ESC) and national energy efficiency schemes. Since the objective of this work was to assess the effectiveness of BEC related rebates, these additional sources were beyond this study's scope.

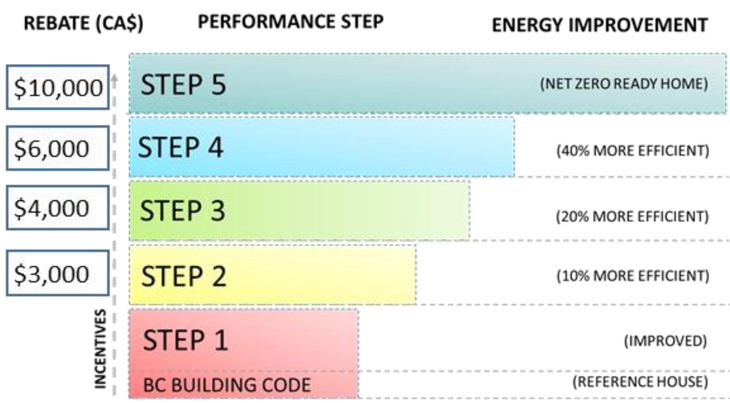
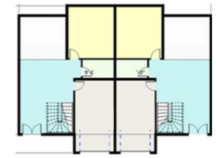
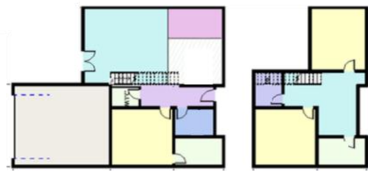
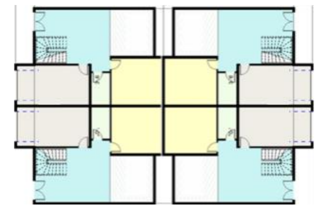
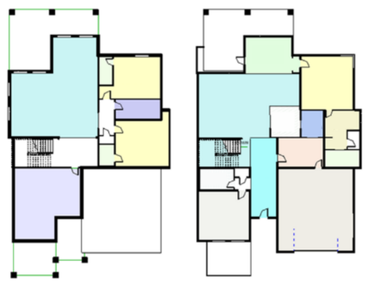
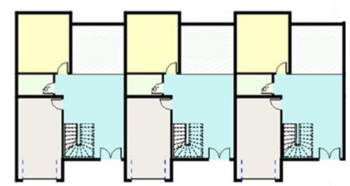
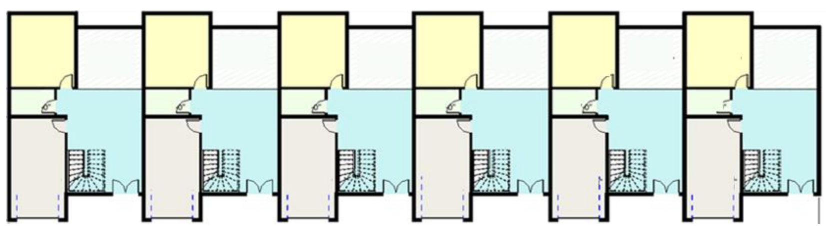


Figure 5-4 Rebates at different performance levels (*Source*:[177,413])

5.3.1 Archetypes and Location

This study considered seven residential buildings based on residential building stock in British Columbia [382,414]. These buildings comprised low-rise residential buildings up to 4-storey high and represented approximately 90% of the residential building stock. **Table 5-5** shows the architectural plans of the houses. The province of BC is divided into 6 climate zones (CZ). Each climate zone pertains to the average heating degree-days (HDD) below 18^{0}C and accounts for the impact of local weather conditions such as temperature, humidity, wind speeds, rainfall and

Table 5-5 Architectural plans of the houses

No.	Archetype	Planimetric view		Archetype	Planimetric view
1.	Small single-family detached home: Single storey on a heated crawlspace, 69.7 m^2($750ft^2$)		5.	Duplex: Semi-detached houses, at least one side is common with another dwelling, preventing heat loss through that side 81.48 m^2 ($877ft^2$)/ unit, 2 storeys	
2.	Medium single-family detached home: 2 storeys, 107.8 m^2 ($1,160ft^2$)		6.	Triplex: Three attached units, 81.48 m^2 ($877ft^2$)/ unit, 2 storeys	
3.	Large single-family detached home: 2 storeys with basement 556.7 m^2 ($5,992ft^2$)		7.	Quadplex: Four attached units, 81.48 m^2 ($877ft^2$)/ unit, 2 storeys	
4.	Six-Unit: Six-attached units, 81.48 m^2 ($877ft^2$)/ unit, 2 storeys				

snowfall on the energy performance of buildings [415]. The lowest CZ-4 has an HDD less than 3,000 while the highest CZ-8 has an HDD greater than 7,000 [416].Three cities, i.e. Vancouver (CZ-4 <3,000 HDD); Kamloops (CZ-5 3,000-3,999 HDD) and Prince George (CZ-6 4,000-4,999 HDD), were selected, since they are hubs of major construction activities in BC [412].

5.3.2 Energy Performance Upgrades

New residential buildings built to BC building code 2012 [306] are considered as the base case (**Table 5-6**). Traditional buildings can be made more energy efficient by increasing their energy efficiency and/or use of renewable energy generation systems [417]. **Table 5-7** provides EPUs considered for meeting BC-ESC targets.

Table 5-6 Detail of base case buildings

Energy performance upgrade	Variable	Details	Cost[a] US ($)		Ref.
Wall Insulation (WL)	R30	-Blanket Insulation kraft faced fiberglass, 9" thick, R30, 11" wide	1.43	/ft^2	[386]
Roof Insulation (RF)	R40	-Blown Insulation Ceiling with 16" thick	2.57	/ft^2	[386]
Windows (WN)	Double	-DG+ 1 HM 88 Low E 20 hard Wood Krypton 9 mm	43	/ft^2	[289]
Space Heating (SH)	92.5 AFUE	-Payne (PG92SCS) 60000 btu AFUE 92.1% Natural Gas &	961.84	1 unit	[289]
Heat recovery ventilator (HRV)	No HRV				
Domestic Water Heater (DHW)	Gas tank	-Rheem (630083) Natural gas hot water EF: 0.59	547	1 unit	[289]

Table 5-7 Details of energy performance upgrades

	Variable	Details	Cost[a] US ($)		Ref.
WL	R40 R60	-Blanket Insulation kraft faced fiberglass, 12" thick, R38, 11" wide -Blanket Insulation kraft faced fiberglass, 18" thick, R38, 11" wide	1.8 4.03	/ft^2	[386]
RF	R70 R100	-Blown Insulation Ceiling with 20" thick -Blown insulation Ceiling with 40" thick	5.14 6.56	/ft^2	[386]
WN	Triple	-TG+ 2 coating Low E 20 hard Vinyl Krypton 9 mm	47.25	/ft^2	[289]
SH	98 AFUE	-Payne (PA14NC) 34000btu 14SEER Split A/C	1,570	1 unit	[289]
HRV	70% HRV	-Lifebreath METRO Series	849		[418]
DHW	Electric tankless Gas tankless Electric DWHP	-Rheem 36kW Electric tankless -Instantaneous, tankless, gas water heaters, Natural gas/propane, 6.4 GPM -GeoSpring™ hybrid electric water heater, 303 L, EF 3.14, Electricity-based	964 1,250 1,322	1 unit	[289] [289] [263]

Air-tightness was kept constant for the base case and upgraded residential archetypes. This constant value was considered mainly due to: (a) lack of validated cost data related to different levels of air-tightness and (b) to remove uncertainty related to the quality of construction that affects air-tightness value. Previous researchers have also avoided air-tightness as a variable to avoid a potential source of inaccuracy in the building model [384,419]. Airtightness value of 0.6 Air Changes per Hour at 50 Pascal was kept so that higher steps of BC-ESC are achievable.

5.3.3 Cost Data

Cost data for the EPUs was collected from existing literature, RSMeans (2019) database and local suppliers [386]. The cost of EPUs varies for the three cities. Hence, in order to represent cost on a uniform scale, the cost of EPUs were shown in US national dollar values (conversion rate year: 2020). Utility energy rates were uniform for the three cities as they were supplied from the same utility. Electricity and natural gas are the dominant energy use sources in BC. The rate structure of these two sources is provided in **Table 5-8**. Among different taxes and charges, the carbon tax on natural gas is especially high and has been increasing per year since 2008 based on BC carbon policy [137]. In fact, the rate of the carbon tax in BC surpassed the natural gas energy rate in 2013 [420]. In addition to these, a 5% discount rate was adopted based on previous studies on residential buildings in Canada [263].

Table 5-8 Details of Electricity and Natural Gas Utility Rates (*Source*: FortisBC [421])

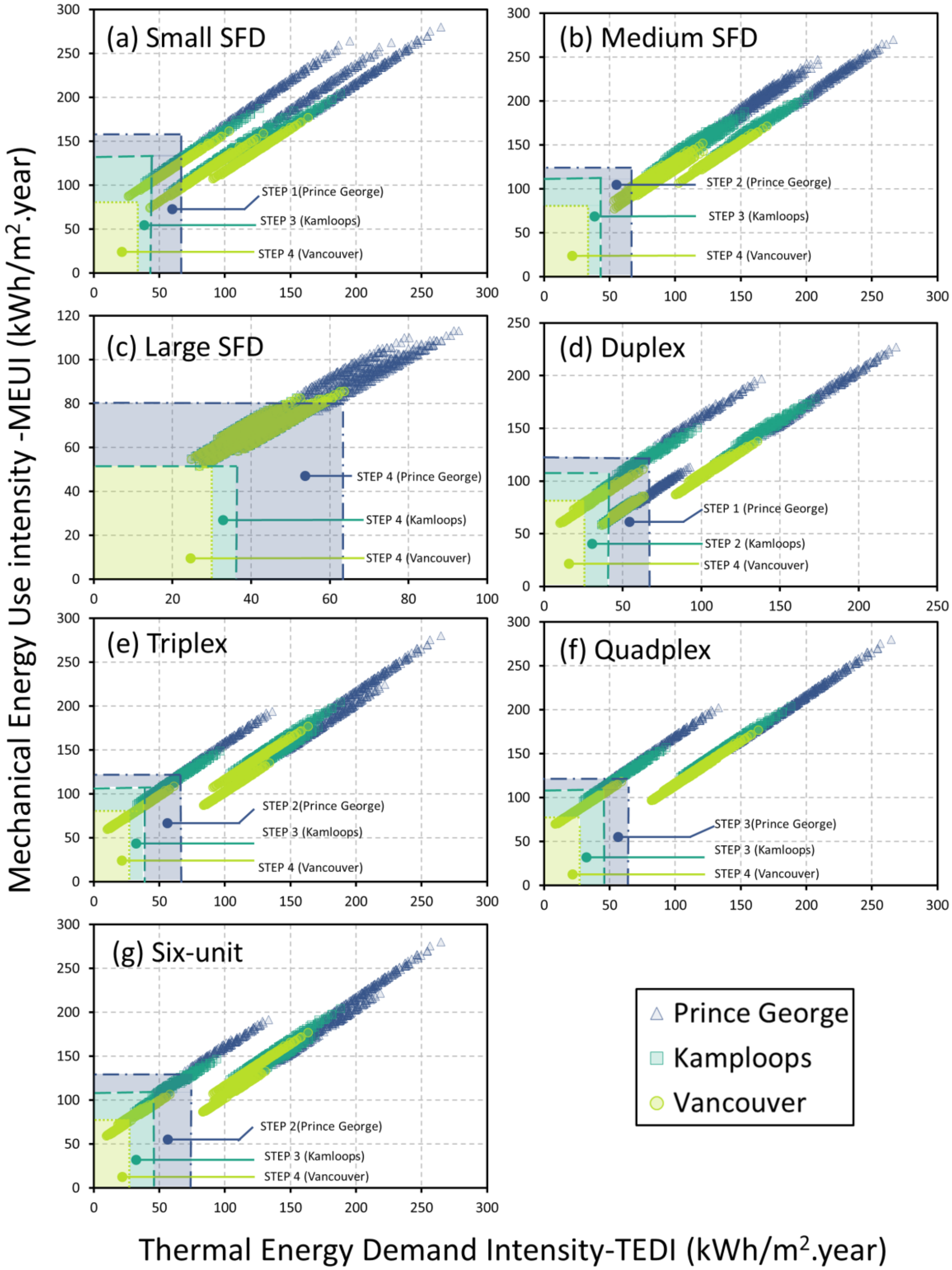
Energy source	Charge	Parameter	Value
Electricity	Delivery charges	Basic daily charge	30 days at 0.4085 CA$/day (0.31 US$/day)
	Commodity charges	Electricity used Block 1: ≤1,600 kWh	10.799 CA¢/ kWh (8.26 US¢/kWh)
		Electricity used Block 2: >1,600 kWh	14.320 CA CA¢/ kWh (10.95 US¢/kWh)
	Taxes	Goods and Services Tax	5% of a amounts
Natural Gas	Delivery charges	Basic daily charge	30 days at 0.4261 CA$/day (0.29 US$/day)
		Delivery	4.596 CA$/GJ (3.51 US$/GJ)
	Commodity charges	Storage and transport	1.019 CA$/GJ (0.78 US$/GJ)
		Cost of gas	2.279 CA$/GJ (1.74 US$/GJ)
	Other charges and taxes	Municipal operating fee	3.09% of a amounts
		Carbon tax	1.9864 CA$/GJ (1.52 US$/GJ)
		Clean energy levy	0.40% of a amounts
		Goods and Services Tax	5% of b amounts

5.4 Results and Discussion

The present research provides a comprehensive methodology to evaluate incentives' performance for achieving compliance with an advanced residential building energy code. The methodology is demonstrated through a case study of incentives (rebates for the specific case study) applicable to seven residential archetypes. It should be noted that the results determined here are very specific to the archetypes, location and building energy code considered; since the results will vary with local environmental and economic conditions. Here, an attempt is made to examine the variation of the effectiveness of these incentives and generate trends that can help policymakers generate tailored incentives.

5.4.1 Energy Performance Upgrades

Energy performance upgrades are known to decrease the energy and GHG emission of buildings. In this case study, the seven archetypes are first modeled in BEopt based on BC Building Code 2012 requirements and represent base cases for the study. These basic energy models were upgraded with EPUs provided in **Table 5-7** to run an extensive parametric analysis. The parametric analysis aimed to shortlist the EPUs combination that could help achieve the highest code compliance level possible. In this regard, a total of 432 energy simulations are run for each house at each location. This analysis considered the impacts of individual EPUs as well as their combinations in reducing energy performance. The TEDI and MEUI values for each archetype are then calculated using energy metrics. A total of 432 energy simulations are run for each detached house, while 288 different simulations are run for each attached house and separately for each location. The TEDI and MEUI values obtained for each archetype are shown in **Figure 5-5**. The same EPUs combination performed better for Vancouver's milder climate compared to Prince George's much colder climate. As shown in **Figure 5-5** (c), the resulting TEDI and MEUI points overlapped for large homes, especially for Vancouver and Kamloops. For the majority of the archetypes, two clear clusters are observed for EPUs combinations provided. The TEDI and MEUI values for various EPUs were compared with code requirements (Appendix F, Table F1). The color-coded shaded area represents the maximum BC-ESC level satisfied by EPUs combinations for the tested cities. All the points falling in the shaded region represent the possible EPUs used for code compliance of each archetype. It is observed that the same combinations of EPUs that perform well for a particular archetype located in a lower CZ also perform well for a more extreme



Note-Each graph represent single archetype tested at three locations defined by different colors. The points represent TEDI and MEUI performance of EPUs combinations. The shaded area represent the maximum code level achieved by house under different climate zones. SFD: Single family detached

Figure 5-5 Code compliance levels achieved by residential archetypes under EPUs combinations climate. However, the resulting energy savings vary and will result in different economic and environmental impacts.

Interestingly, the same EPUs combination also resulted in the archetypes complying to different levels despite more stringent requirements for warmer climates than colder ones. Hence, in most cases, the best performing EPUs resulted in Prince George's homes falling at much lower levels than Vancouver and Kamloops. The only outlier are EPUs for large SFD, which can achieve Step 4 compliance in all three tested locations. Hence all archetypes in Vancouver are eligible for higher rebates and large SFD will be eligible for the highest rebates compared to other archetypes at other locations. In contrast to Vancouver, small and medium SFD in Prince George do not comply with any eligible rebate level. The maximum steps achieved along with rebates for 7 archetypes at three locations are provided in **Table 5-9**. It is seen that all archetypes in Vancouver can achieve Step 4 while the compliance level decreases in colder climates. Most homes in Kamloops can achieve Step 3, while medium SFD performs worst and only achieves Step 2. Likewise, homes in Prince George also comply to a lower level, with most homes achieving Step 1 or Step 2. This disparity in steps achieved is due to higher savings achievable in warmer climates and differences in the code specified TEDI and MEUI intensity targets for different archetypes and locations.

Table 5-9 Applicable rebates

Location	Archetype	Small SFD	Medium SFD	Large SFD	Duplex	Triplex	Quadplex	Six-Unit
Vancouver (CZ 4)	Compliance level	Step 4	Step 4	Step 4	Step 4	Step 4	Step 4	Step 4
	Rebate (CA$)	6,000	6,000	6,000	12,000	18,000	24,000	36,000
Kamloops (CZ 5)	Compliance level	Step 3	Step 2	Step 4	Step 3	Step 3	Step 3	Step 3
	Rebate (CA$)	4,000	3,000	6,000	8,000	12,000	16,000	24,000
Prince George (CZ 6)	Compliance level	Step 1	Step 1	Step 4	Step 2	Step 2	Step 3	Step 2
	Rebate (CA$)	0	0	6,000	6,000	9,000	16,000	18,000

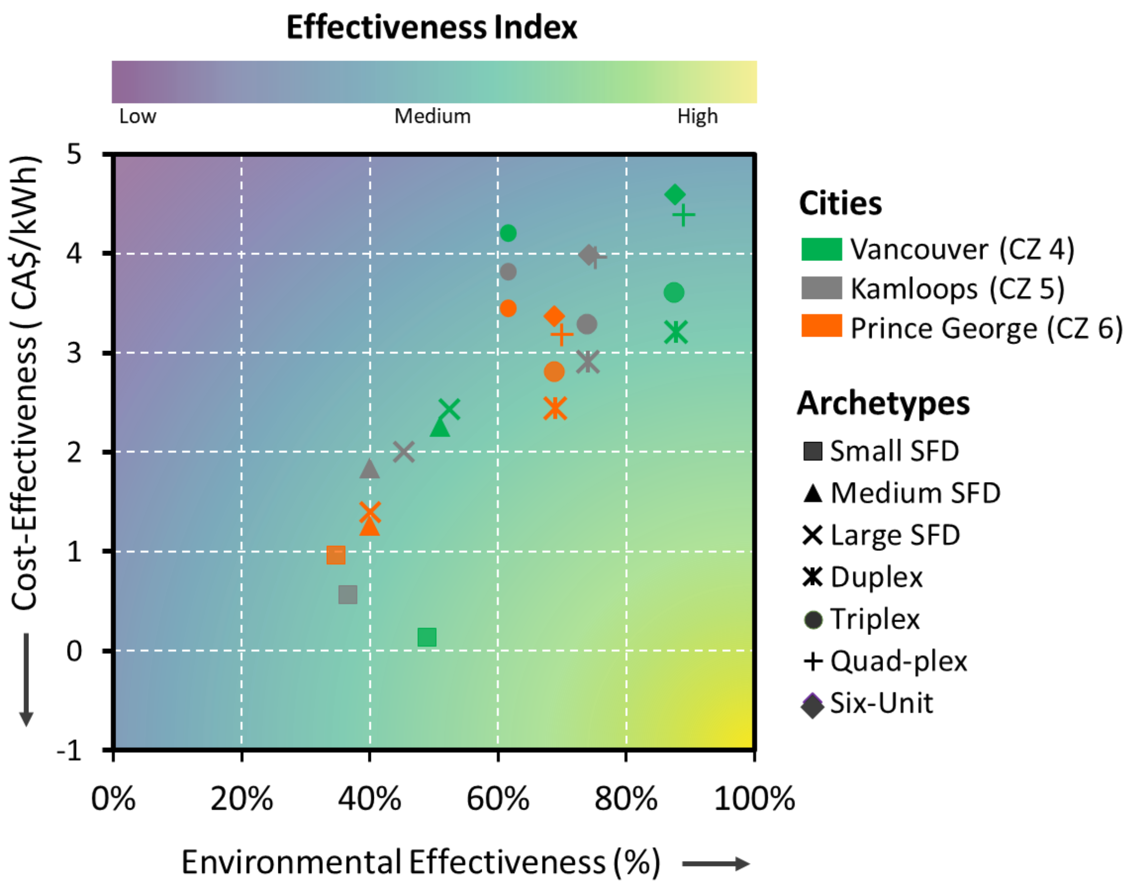
Note- SFD: Single family detached; CZ: Climate zone

5.4.2 Financial Incentives Effectiveness Index

Figure 5-6 provides the effectiveness index matrix generated for the seven archetypes. The results of code compliance levels were used to determine energy savings and GHG reductions achieved and the best performing EPUs were selected to determine the applicable rebate amount. The operational energy savings were used to determine savings in operational bills and added in the life cycle costing model to determine the extra expenditure required for EPU. It is observed that archetypes located in Vancouver provide higher environmental effectiveness that ranges from about 50% to 90%. However, for most cases, the cost-effectiveness for the applied incentives was lower for homes located in the warmer climate of Vancouver despite showing higher energy savings. This result is due to higher construction and investment costs in Vancouver compared to the other two cities. Likewise, under the applied incentives, the archetypes n Kamloops had higher environmental effectiveness but required more expenditure to achieve energy savings than Prince George. The cost-effectiveness for Kamloops showed the lowest value for a six-unit attached home and required 4 CA$ to save a kWh energy. The cost-effectiveness of Prince George ranged from about 1 CA$ to 3.5 CA$ to save a kWh of energy.

It is also observed that compared to SFD, the cost and environmental effectiveness showed similar trends in attached homes for each location. The attached homes also show higher GHG reduction potential than SFD and required more expenditure resulting in their lower cost-effectiveness. These results have important implications for the energy policies and highlight the need to consider local building archetypes and trends in construction. For instance, if the main aim of building energy policy is to reduce the energy expenditure of the building stock, then colder climates would achieve more significant energy savings at lower costs compared with similar archetypes in milder climates. However, if the policy aims to reduce GHG emissions, emphasis should be on attached homes in all climates.

The local neighborhood design will also be essential to guide incentive design and deployment. Currently, the residential sector in Canada is dominated by single-family detached homes [422]. The distribution of these archetypes varies from one location to another. For the three cities number of SFD homes have a higher percentage in Kamloops and Prince George, while for Vancouver, they only occupy up to 20% of the archetypes. This distribution may require more incentives to be directed at SFD homes located in Kamloops and Prince George. In comparison, more incentives may be assigned to Vancouver attached homes to yield higher benefits. Therefore, some archetypes may even be eliminated from the incentive program to yield maximum cost and environmental benefits depending upon the local building stock profile.



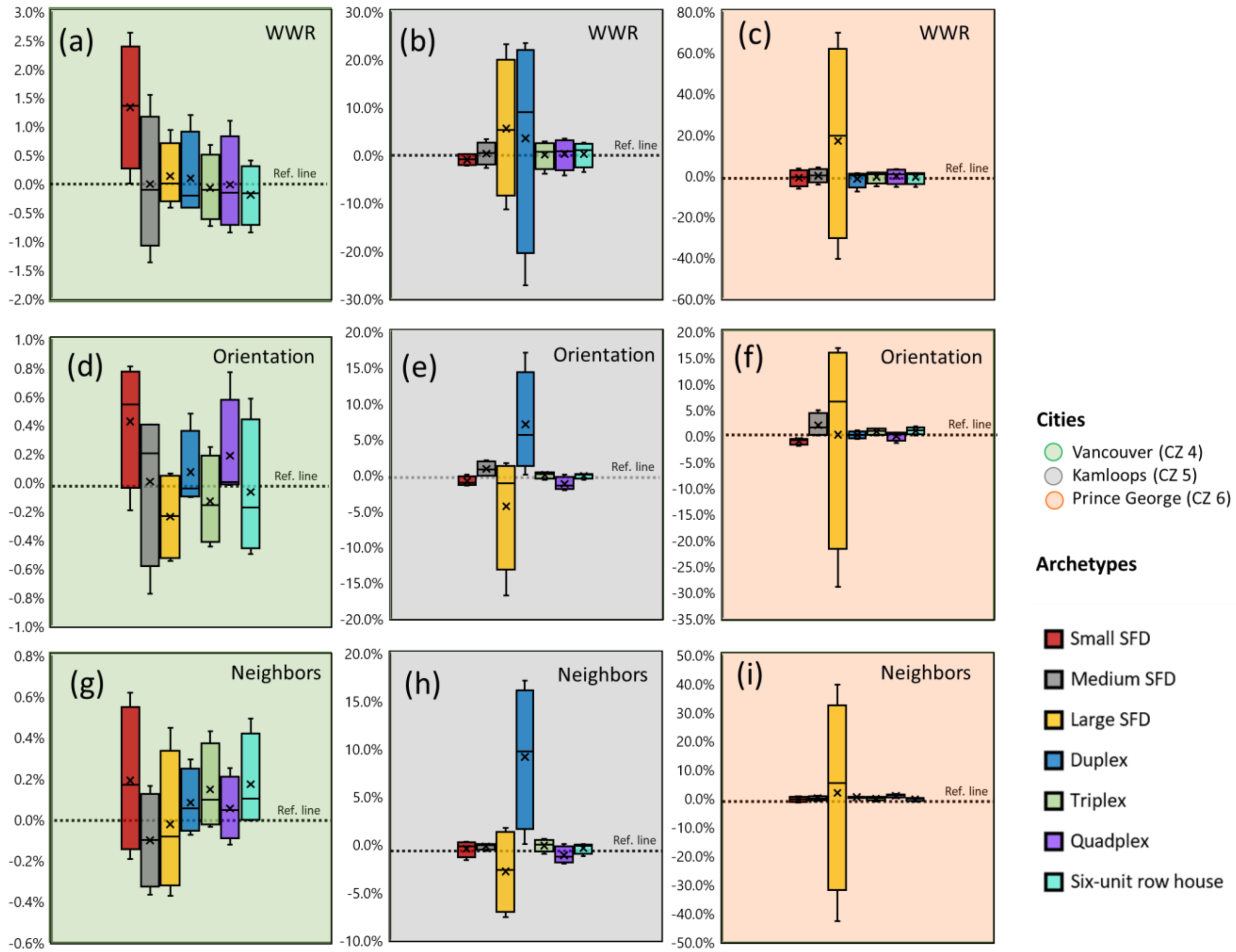
Note- SFD: Single family detached

Figure 5-6 Effectiveness Index for tested residential archetypes

5.4.3 *Sensitivity Analysis*

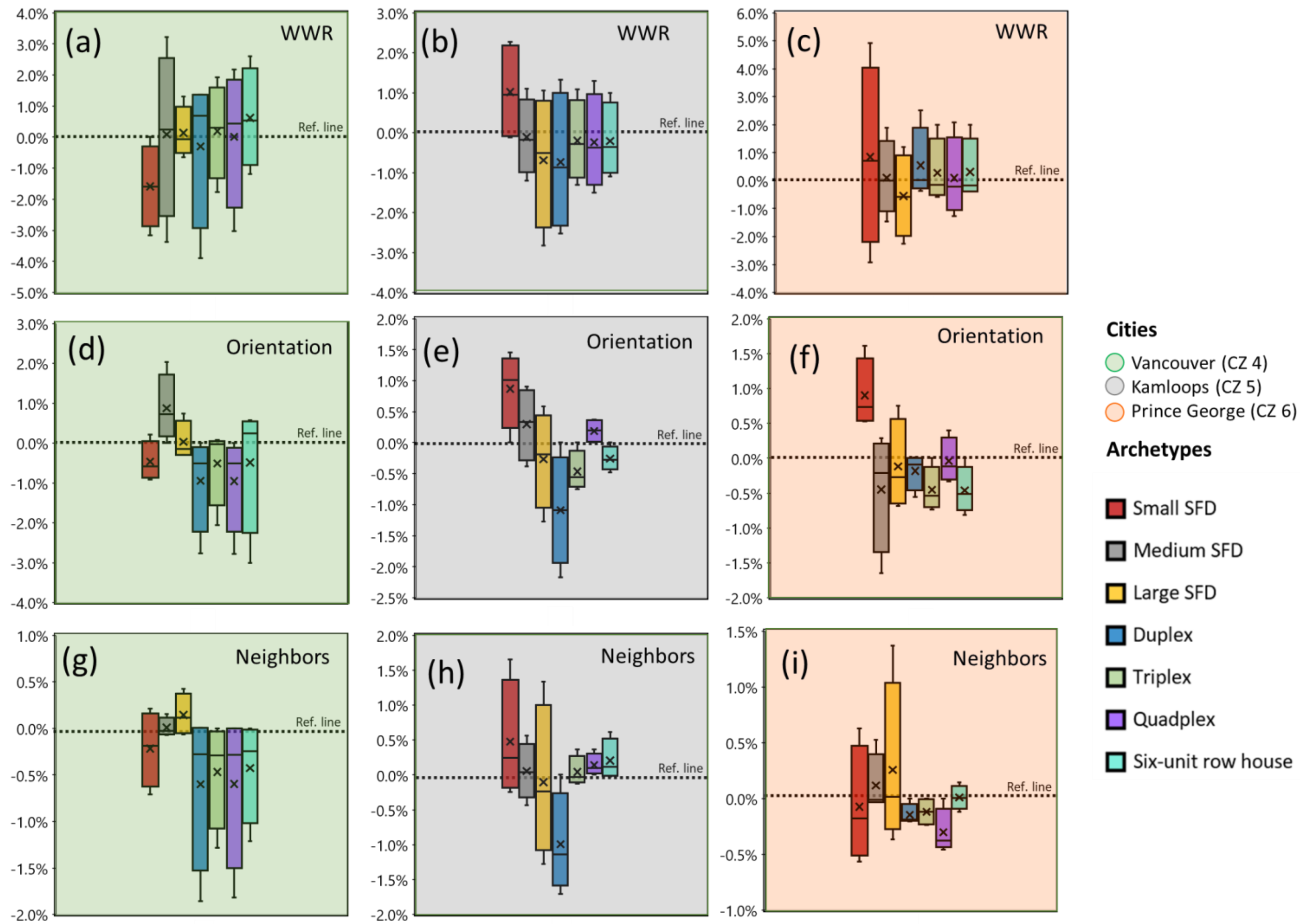
This section represents the results of sensitivity analysis to the design and economic factors. These factors are explicitly considered for the Canadian context and the results should be applied with necessary precautions and modifications.

<u>*Design factors:*</u> **Figure 5-7** and **Figure 5-8** show the variation in cost and environmental effectiveness, respectively, for the three design factors: window-to-wall ratios (WWR), building orientation and distance from neighboring buildings. In these figures, the horizontal axis of the



Note- SFD: Single family detached: WWR: Window to wall ratio; CZ: climatic zone

Figure 5-7 Sensitivity Analysis: Impact of design factors on cost-effectiveness



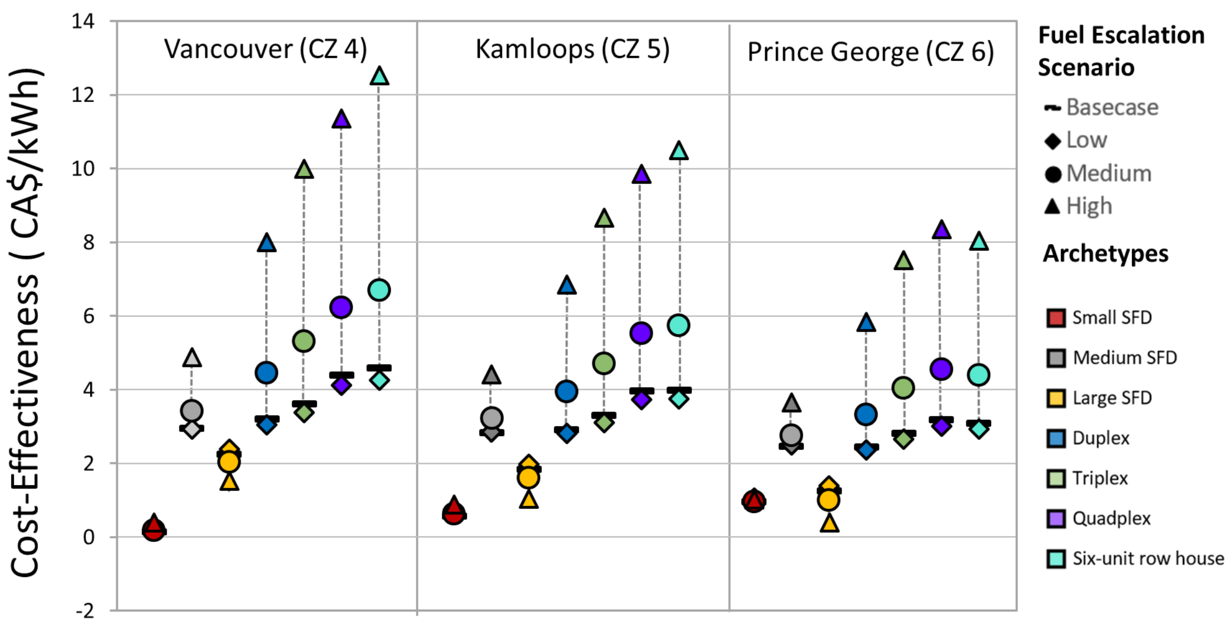
Note- SFD: Single family detached: WWR: Window to wall ratio; CZ: climatic zone

Figure 5-8 Sensitivity Analysis: Impact of design factors on environmental effectiveness represents the seven archetypes, while the vertical axis represents the percentage variation in cost and environmental effectiveness for the latter figure. Two general observations can be made from these figures about the sensitivity of effectiveness. Firstly, the variation is more significant in cost-effectiveness (ranges -56--69%) for different archetypes than environmental effectiveness (ranges -4--34%). Secondly, the variation is more pronounced for archetypes located in colder climates of Kamloops (range -32--12%) and Prince George (range -56--69%) compared to Vancouver (range -4--3%). Though all the design parameters impact archetypes' performance, the variation is most pronounced in medium and large SFD. This variation is also a reflection of the heat losses possible due to large wall areas. These changes are mainly reflected for homes in Kamloops and Prince George with colder climates and thus more heat losses.

When consequent cost and environmental effectiveness are also changed. This finding is important because existing neighborhoods in Kamloops and Prince George have more than 60% of the residences as single-family detached homes [422]. These trends of SFD homes construction are predicted to continue, as seen from BC statistics of year 2020, where more than 9,600 new SFD were registered despite the low economic progress during the COVID-19 pandemic. Compared to multi-unit residential homes, whose registrations decrease by 37.1 %, the SFD home saw an increase of 11.5% in the year 2020 [423]. Overall, the effects of design factors on effectiveness are essential, especially when considering the effectiveness of rebates at a building stock level.

The current work explored sensitivity analysis to individual design factors. In most cases, these factors will interact with each other to reinforce or decrease the effectiveness of rebates in achieving desired targets. Furthermore, these impacts may seem insignificant in some cases for single archetypes, but their impacts will be compounded when considered at community levels. Therefore, the impacts of design factors cannot be ignored from a policy perspective.

Economic factors: Two leading economic factors, energy escalation price and a carbon tax on fossil fuels, were considered in the study. Previous researchers have shown that energy savings (and hence savings on energy bills) are mainly affected by the local energy prices [368]. depicts the impact of energy price scenarios on cost-effectiveness. As expected, the increase in **Figure 5-9** energy price reduces the effectiveness of rebates. However, the degree of impact varies significantly with archetype and location. More variation is observed for attached homes, with the impact is more pronounced for homes located in Vancouver than Kamloops and Prince George. These results are due to higher investment requirements for homes in Vancouver compared to the colder and smaller cities. Likewise, it is seen that as the number of attached units increases, the cost-effectiveness decreases. For instance, for duplex homes in Vancouver, about 3 CA$ is required to save a kWh of energy and as the energy price rises to the highest scenario (10% rise in electricity and 8% rise in gas prices), an additional 5 CA$ need to spend to achieve the same amount of savings. In the same vein, the six-unit attached house sees a reduction in cost-effectiveness and an additional 8 CA$ are needed to reduce a kWh of energy. In contrast, attached homes do not show a significant decrease in cost-effectiveness and a maximum 2CA$ is required to achieve the same amount of savings in these homes. This difference may not be significant compared to attached homes but can be magnified depending upon local building stock. As stated in the previous section, SFD homes dominate building stocks in Kamloops and Prince George. Furthermore, it was estimated that EPUs for medium SFD in Prince George were not eligible for any rebate (**Table 5-8**). Therefore, the impacts of fuel price escalation need to be accounted for when allocating incentives, and the archetype dominating local building stock should become part of future rebate policy.

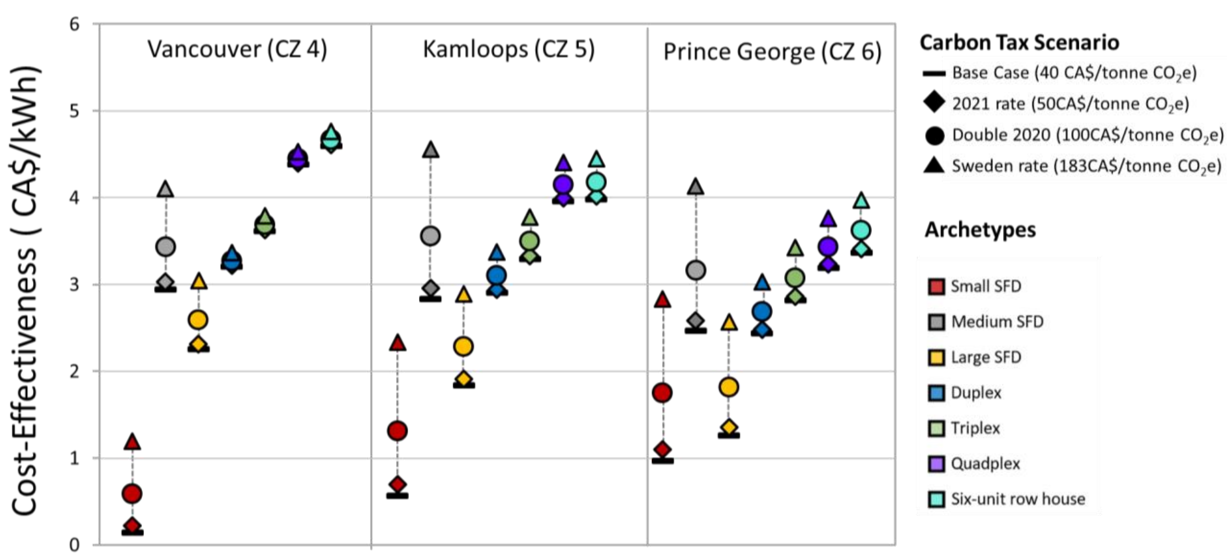


Note- SFD: Single family detached; CZ: climatic zone

Figure 5-9 Sensitivity Analysis: Impact of fuel price escalation on cost-effectiveness

The carbon tax increases fossil fuels prices, thus encouraging the adoption of low carbon technologies and energy sources [424]. Often, the carbon tax is considered a complementary instrument that can influence the impact of available rebates. BC is one of the few regions of the world where a carbon tax has been actively applied to address climate change. The application of carbon tax in BC is considered a successful policy that reduced provincial carbon emissions [425,426]. Xiang and Lawley [139] noted that carbon tax in BC reduced natural gas use by 7% in the residential sector. Therefore, due to the significance of carbon tax in BC, the impacts of its variation were analyzed.

Figure 5-10 shows carbon tax scenarios for the tested archetypes. It is seen that in contrast to fuel price escalation (**Figure 5-9**), which had high impact on cost-effectiveness related to attached homes, the carbon tax has a more significant impact on SFD homes. In addition, the carbon tax is seen to impact homes in colder cities of Kamloops and Prince George compared to Vancouver. Interestingly, the cost-effectiveness decreases more significantly for small and medium SFD compared to larger homes. In Vancouver, the increase in cost requirements for homes ranges from about 1CA$ for attached homes to few cents in attached homes. The attached homes in Kamloops and Prince George require approximately 2CA$ more dollars while attached homes require about 75CA¢. It is also noteworthy that the decrease in the cost-effectiveness of attached homes at each location is almost uniform. Overall, a carbon tax does not have a significant impact as compared to fuel (electricity and natural gas) price escalation. However, these results indicate that at a very high carbon tax rate, implementation and implementation of more stringent BEC targets may become difficult for SFDs. In short, if more extreme carbon taxes are implemented, there may be a need to revise the number of rebates for SFD homes, especially for low-income occupants.



Note- SFD: Single family detached; CZ: climatic zone

Figure 5-10 Sensitivity Analysis: Impact of carbon tax rate increment on cost-effectiveness

5.4.4 Key Findings

Based on the above results and findings, following implications need to be considered that need to be considered for designing and allocating rebates to yield maximum cost savings and environmental benefits.

Small SFD homes do not significantly contribute to energy and cost requirements, especially for homes in Vancouver, where a more significant portion of archetypes is composed of attached and multi-unit residential apartments. Depending upon the local building stock, the rebates for small SFD can be directed towards larger SFD and attached homes to yield more significant savings.

Medium SFD homes form a large percentage of the residential building stock and require a considerable investment to improve energy efficiency. Especially under COVID-19, which has a disproportionally affected population, the end-users of medium SFD can be unwilling to make significant investments. Under changing economic conditions, there may be a need to direct additional rebates to achieve efficient building stock.

Large SFD construction is standard, especially in newer suburban residential communities. The analysis indicates that the rebates offered on large buildings can offer higher GHG reduction. Furthermore, compared to other archetypes, large SFD shows higher variation under changing design parameters, especially for the colder climate of Prince George. Hence, additional rebates may be needed for large SFD located in Prince George.

Attached homes can provide higher environmental effectiveness under available rebates but require more expenditure to save per unit of energy. There is a need to direct additional financial resources towards these homes because of the more considerable investment required for installing EPUs, increased construction rates and uncertain economic conditions. contribute to energy and cost requirements, and the rebates can be directed towards larger homes to yield greater savings.

5.4.5 Limitations and future direction

Despite an extensive study on many residential archetypes, some cautions need to be considered for adopting our results for other archetypes, locations and economic conditions. A limited number of locally available EPUs were utilized for rebates effectiveness evaluation. Future studies should carefully consider the local context and construction practices during financial incentives assessment. This research was based on virtual buildings simulated on BEopt. Although simulations are powerful techniques, each energy modeling tool has limitations and cannot accurately represent complex built environments. The uncertainty present in these models needs to be accounted for to predict energy performance and ensure BEC compliance accurately. In the same vein, another critical factor that needs to be explored in future studies is the order of interaction among various uncertain parameters (design and economic). This chapter only explored the impact on cost and environmental effectiveness due to changing one parameter at a time (called One-At-a-Time (OAT) or local sensitivity analysis). However, this type of analysis rarely provides the full impact on the output variables [427].Multivariate sensitivity analysis can help determine the magnitude of interaction among input parameters [428]. Therefore, future work on incentives effectiveness should evaluate the interaction among various uncertain parameters.

Another critical limitation was the consideration of standard occupancy profiles, same investment capability and preference of end-users. The next phase of this study will consider the impact of different end-users' occupancy variation and cost constraints on the effectiveness of financial incentives. The overall impact of financial incentives policy should be evaluated at the building stock level using bottom-up energy modeling techniques. The framework was introduced for new buildings. However, it can be modified and applied to retrofit existing buildings by carefully evaluating and classifying existing archetypes. Compared to new houses, existing homes are more complex and will have a more extensive set of constraints that will vary with a local context. Similarly, the seven archetypes represent generic models; a more detailed study should be conducted that utilizes actual buildings and uses their calibrated energy models to study rebates effectiveness. Detailed survey studies will be required to identify the archetypes of the existing building stock and design effective financial incentives. Based on the above results and findings, a set of recommendations are being provided for each archetype that can help in rebates design and allocation to yield maximum cost savings and environmental benefits.

5.5 Summary

The chapter presented a novel methodology to understand the impacts of financial incentives available for new residential buildings. The methodology has the potential to determine the effectiveness of FIs for residential archetypes from end-user's perspective and hence will be useful in the implementation of advanced building energy codes. The main novelty of the methodology is the introduction of a FIs effectiveness matrix. To the best of authors' knowledge, an effectiveness matrix related to FIs of green buildings is still missing from the literature. The methodology consists of three main stages: screening mechanism to determine suitable energy performance upgrade and applicable FIs; evaluation method of effectiveness index; and checking the sensitivity of FIs effectiveness against key design and economic parameters. Parametric analysis of energy upgrades in BEopt and excel based algorithms are used to determine the impact of FIs on cost, energy and carbon mitigation metrics. In this regard, a case study is performed on rebates related to building energy code in British Columbia (Canada) and applied on seven low-rise residential buildings. These archetypes represented approximately 90% of the total residential building stock. Hence a comprehensive evaluation is performed. Results indicate a significant difference in cost and environmental effectiveness with a change in archetype and location. The results further demonstrate the importance of sensitivity factors in effectiveness evaluation. Hence, in order to introduce or improve existing FIs the local context and uncertain parameters related to a particular neighborhood cannot be ignored.

Chapter 6 Rebates' Efficiency at Building and Neighborhood Levels

A version of this chapter is under preparation for a peer-reviewed journal paper, as an article titled "Efficiency of utility rebates: A case study of British Columbia" that will be submitted to the Elsevier journal *Journal of Cleaner Production* in June 2021.

6.1 Background

In **Chapter 5**, comprehensive energy and cost models were generated to determine rebates' "effectiveness index" for different residential archetypes. The proposed methodology was built from the end-user's perspective and restricted to individual buildings. The rebates are part of government limited budgetary resources [429] and need to be allocated strategically to ensure maximum efficiency. The problem of climate change adds to the current management and strategic challenges for the government and the utilities. Hence, it is imperative to utilize the resources efficiently and allocate them to attain maximum benefit. Adopting economically feasible rebate structures can help utilities meet the growing energy needs and meet the desired mitigation goals. To allocate resources, the performance of buildings under these rebates must be assessed for the amount of energy saved, the carbon mitigation potential and consequent preference of the stakeholders. Rebates are the most common FIs offered by the utilities in Canada [21,132]. Hence, it is essential to determine how the current rebate structures are performing and which building archetype can perform the best under the existing allocation system. In recent years, policymaking for climate change has shifted from the impact of individual buildings towards local and regional levels [430]. Therefore, the offered energy efficiency rebates need to be efficient at both building and regional levels. Like effectiveness, efficiency is a core criterion for evaluating FIs policy. Efficiency can provide quantitative information for decision makers and help in strategic allocation. Efficiency can be defined as the ratio of outputs obtained to the invested resources. Energy-related decisions can be defined as the ratio of outputs, such as energy performance, emissions; to inputs such as investment and material consumption [32]. Therefore, the "efficiency" of rebates can help evaluate the quality of outputs with minimum use of resources [431].

Among efficiency evaluation methods, data envelopment analysis (DEA) has been especially popular for its non-parametric nature, capability to use multiple inputs and outputs, eliminating the dependence on expert judgments and ease of application [432–434]. DEA has been applied for evaluating the efficiency of subsidies in agriculture, tourist industry, business, power plants and transportation [434–437]. Likewise, DEA has also been used to select optimal energy performance upgrades and to benchmarking green cities and regions [438–441]. The method has been used successfully in identifying the most efficient measure and in allocating resources. Hence, DEA method can be adopted to evaluate efficiency of rebates offered for energy efficient buildings.

A government subsidy program for residential buildings' overall economic efficiency depends on of the government and private investors' perspective [28]. The subsidy providers are interested in allocating minimum resources, i.e., subsidy amount that will yield the highest energy and GHG emission reduction. At the same time, the investors’ want to spend the least-cost amount that can enable the government-mandated targets [28]. Hence, evaluating both government and investors' perspectives is needed to assess a subsidy program's success. Among subsidies, rebates provided by utility companies and governments are the most popular policy instruments used globally [132]. Studies on efficiency evaluation of the subsidies have largely been based on surveys that have been often performed at national levels. Hence, there is a shortage of the impact of the efficiency of rebates at the building and neighborhood level.

This chapter proposes a methodology for evaluating the efficiency of rebates for energy-efficient residential buildings at building and neighborhood levels. The specific objectives of this research are:

(1) Assessment of technical efficiency of rebates at building and neighborhood levels;
(2) Assessment of end-user’s investment efficiency at building and neighborhood levels;
(3) Comparison between technical efficiency of rebates from government and end-user’s perspectives.

The assessment provides unique insights to the policymakers regarding the challenges and opportunities in the existing subsidy allocation procedure and provides effective policy design guidelines.

6.2 Methodology

A three-phase methodology is introduced to determine efficiency from investors and government perspectives. The phases are (1) data collection, (2) data processing and (3) data analysis. The methodology is illustrated for financial rebates on the Building Energy Step Code (BC-ESC), Canada. The methodology is illustrated for financial rebates on Building Energy Step Code (BC-ESC), Canada [177]. Subsequently, the proposed research methodology is explained in **Figure 6-1**.

6.2.1 Phase 1: Data Collection and Processing

The energy, cost and GHG emission calculated at building and neighborhood levels are used to develop DEA indicators and DEA models. Phase 1 consisted of three main components (a) data collection; (b) energy performance upgrades (EPUs) selection and (c) energy performance and cost evaluation at neighborhood levels. Among these components, the first two components, i.e. (a) data collection and (b) EPUs selection, are similar to Section 5.2.1 and Section 5.2.2, respectively in **Chapter 5**. Hence, only details on the second and third phase of this methodology are provided in this section.

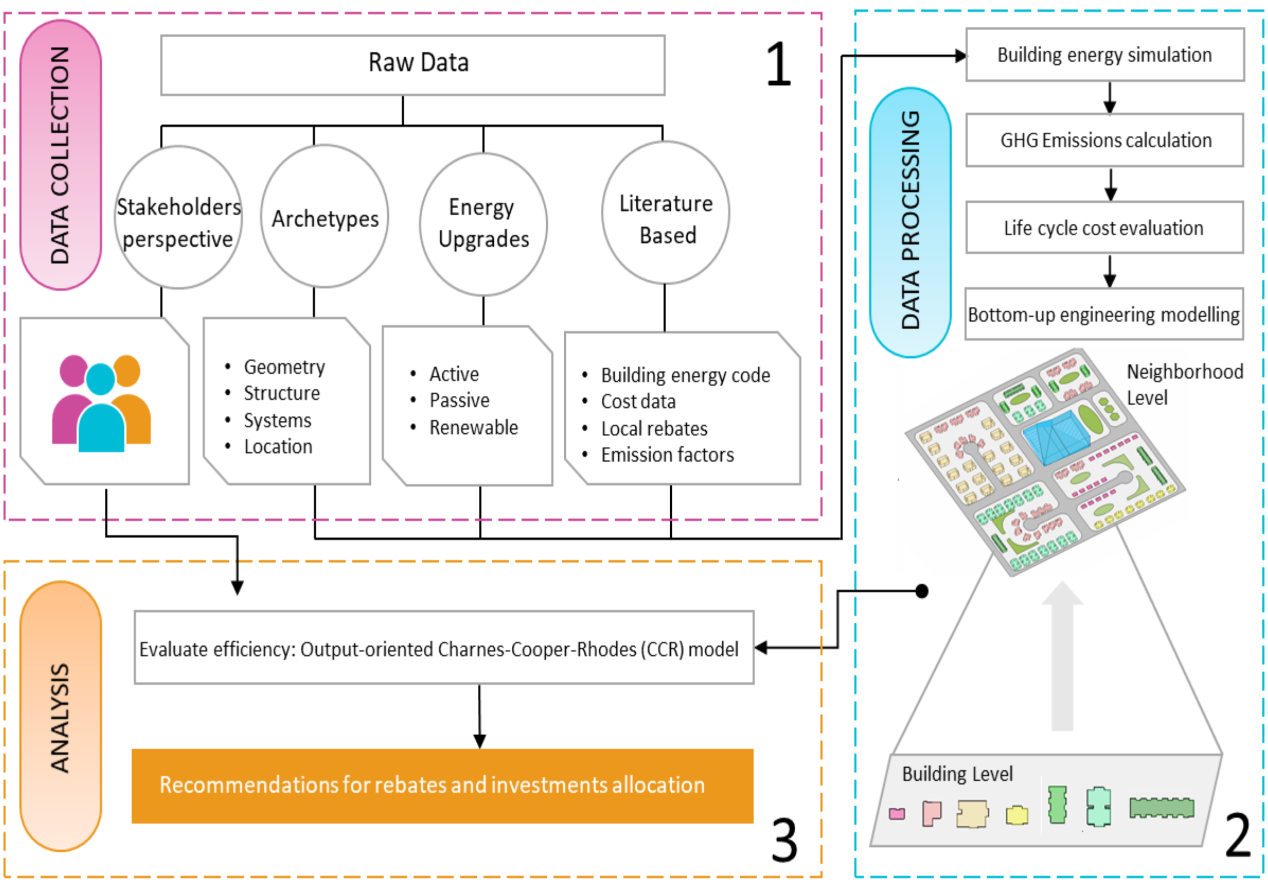


Figure 6-1 Research Methodology

Assessment of building stock performance at regional scales can help derive suitable incentive policies. Despite the importance of regional level building stocks for effective policy design, few studies have evaluated resource consumption and performance of residential building stocks [397]. Residential buildings for a specific region or country can be classified into archetypes based on their form, built and use. Building stock models at neighborhood levels can be constructed based on previous literature, surveys and national and regional building energy codes [442]. Archetypes of existing buildings can be based on regional and national surveys. Examples of such databases are the US Census Bureau's American Housing Survey (AHS) [443], the DOE Residential Energy Consumption Survey (RECS) in the United States [444] and the Statistics Canada 2016 survey in Canada [422]. Some databases contain information on a number of countries, such as the Typology Approach for Building Stock Energy Assessment database (TABULA) that represents residential archetypes for 13 European countries [445].

Energy stock models can be prepared through top-down or bottom-up modelling approaches. Top-down modelling is mostly based on econometric techniques but are unable to capture the impact of new technologies and policies. On the other hand, Bottom-up modeling utilizes statistical or engineering techniques that estimate end-use energy aggregation to find building stock performance [446]. Since these models are based on building physics, census surveys and other statistical datasets, they can be successfully used to predict the energy of past, present and future residential building stocks [447–449]. Hence, bottom-up modelling can better represent the impact of new technology or policy compared to the top-down modelling approach [450]. Bottom-up modelling commonly uses weighting approaches for determining building stock performance at regional or national levels [275,450]. Hence, this research uses bottom-up modelling using the weighting approach.

The building stock models at neighborhood levels are generated on a method similar to Krarti (2018) [446]. The specific method followed to achieve neighborhood-level results are:

(1) Classify building stock based on geometry, systems, structural types and location factors.

(2) Construct building energy models based on archetypes determined in the previous step. The number of energy models constructed is proportional to computational time; hence, an appropriate number of models representing the largest portion of building stock is selected.

(3) Evaluate end-use energy for each archetype using the BeOPT tool.

(4) Determine neighborhood-level energy use by aggregation of archetypes end-use energy through a weighting technique based on archetype distribution.

6.2.2 Phase 2: Data Analysis

Phase 2 Phase 2 consisted of three main components (a) evaluation of indicators, (b) assessment of decision-making units (DMUs) and (c) application of the DEA model.

(a) Evaluation of Indicators: Three key indicators were selected, each for government and investors' perspective based on existing literature [28,132,263,451,452]. The government perspective considered "rebates" as inputs and "energy saved" and "GHG emissions reduction" as outputs. Investors' perspective included "additional life cycle costs (dLCC)" as input and "energy saved" and "GHG emissions reduction" as outputs. These are illustrated in **Table 6-1** and described in the following sections.

Table 6-1 Variables for DMUs

Perspective	Variable	Indicator	Description
Government	Input	Rebates (CAD$)	Rebates are an important investment from the government and utility providers.
	Output	Energy saved (kWh/year)[a]	Energy saved is considered to be a cost-effective and easily applicable method to mitigate climate change[453]. In addition to saving the planet, reduction in energy use or increased energy efficiency of residential buildings has a number of co-benefits that include reduced energy bills for consumers, better air quality, health and well-being of occupants. Due to the vast importance of the topic, the energy efficiency has recently become part of efficiency evaluation studies.
		GHG reduction (tCO_2-eq./year)[b]	Energy savings cannot completely represent the benefit gained to the environment. Hence GHG emissions reduction are an essential factor.
Investor	Input	Difference in life cycle cost (CAD$)	Previous studies show that the implementation of BEC targets includes additional investment from the investors (end-users or developers) perspectives. This is the most important investment and decision parameter from the investors' perspective.
	Output	Energy saved (kWh/year)	See ([a])
		GHG reduction (tCO_2-eq./year)	See ([b])

(b) Assessment of Decision making units (DMUs): Environment efficiency was determined at (a) building and (b) neighborhood level. At the building level, the DMUs are different residential archetypes, while at the neighborhood levels distribution of these archetypes per unit area is DMUs. At the neighborhood level, the archetypes depend on local weather, usage and economy of the area. For example, multi-unit residential buildings dominate metropolitan areas, while suburban areas with new construction are predominantly single-family detached homes. Hence, the efficiency of rebates will vary both at building and neighborhood levels.

(c) Application of DEA model: DEA technique was developed by Charnes, Cooper & Rhodes [432] based on Farrells work [454]. DEA utilizes the basic efficiency concept and uses it to convert multiple inputs and multiple outputs into a single efficiency reports [455]. The DEA method has the advantage of requiring no specific functional form. As such, qualitative and quantitative factors can be evaluated. Efficiency is assessed based on the frontier created by compared DMUs. Existing MCDM methods can perform subsidy allocation; however, weighing all of them is a big challenge due to numerous environmental and economic parameters. Hence, traditional allocation procedures can fail if a wrong set of weights is adopted. The utilization of DEA is proven to effectively address this problem and allocate subsidies in other areas [455].

Models developed by Charnes, Cooper & Rhodes (CCR) models evaluate the efficiency of DMUs based on self–evaluation under existing rebates conditions [432]. Among various DEA models, CCR-output based model has been frequently used for assessing the efficiency of subsidies [435,456]. Input-based models are more frequently used in literature due to their easier interpretation; however, output-based models are more advantageous for subsidies as they will enable maximum benefit from available resources [38]. Hence, this research used a standard CCR-output model for efficiency evaluation. The CCR model aims to maximize the outputs with a fixed sum of inputs and is determined by Equation 6-1 subject to the constraints defined below.

$$max\theta_p = \frac{\sum_{r=1}^{s} u_r y_{rp}}{\sum_{i=1}^{m} v_i x_{ip}} \qquad \textit{Equation 6-1}$$

s.t.

$$\frac{\sum_{r=1}^{s} u_r y_{rp}}{\sum_{i=1}^{m} v_i x_{ip}} \leq 1 \qquad j=1,2,3\ldots n,$$

$$u_r \geq 0 \qquad r=1,2,3\ldots, s,$$

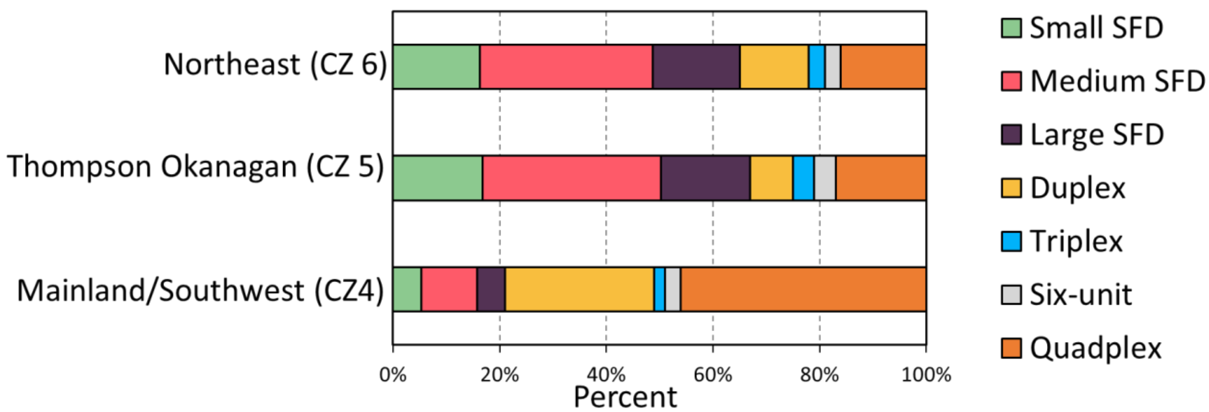
$v_i \geq 0$ i=1,2,3…, m,

where u_r and , v_i are the inputs and outputs weighting vectors for a DMU j, respectively. The DEA method distributes DMUs into two main groups: efficient and in-efficient. The DMUs that depict the value of efficiency as "1" are efficient and those with lower value fall will be inefficient. A performance-based perspective is considered [435] for this research; hence, buildings and neighborhoods with higher efficiency from a government perspective will be assigned more significant rebates compared to those with low efficiency. Similarly, from investors' perspectives, archetypes and neighborhoods that are efficient would be the preferred investment choice for investors. The residential building archetypes are fixed and cannot be changed while the amount of rebates and investors costs can be reallocated. Therefore, output based model was considered to evaluate efficiency.

The individual DMUs performance is reflected on overall group performance. In this regard, best performers assert positive impacts while negative impacts are influenced by weak DMUs [437]. The research method proposed by Ang et al. (2018) [437] or group efficiency evaluation has been used. The inputs and outputs for individual DMUs were first aggregated to determine the group inputs and outputs. Then the CCR-output model was applied to assess group efficiency. Therefore, this research investigated the efficiency at two levels and compares how the efficiency varies between the two perspectives. This will help both policymakers design rebates that will yield maximum benefit and investors direct their investments at locations that will yield more energy savings and GHG emission reductions.

6.3 Methodology Demonstration

The case study considers the rebates available for building energy step code in British Columbia (Canada), BC Energy Step Code. Currently, the residential sector in Canada is dominated by single-family detached homes [422]. Seven archetypes representative of common residential archetypes in Canada are selected as DMUs at the building level. At the neighborhood level, three DMUs are used that represent the distribution of these archetypes in three climate zones: Mainland/Southwest (CZ4), Thompson Okanagan (CZ 5) and Northeast (CZ 6) (**Figure 6-2**).

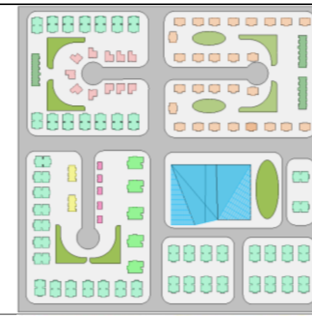
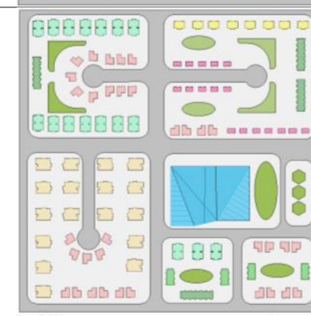
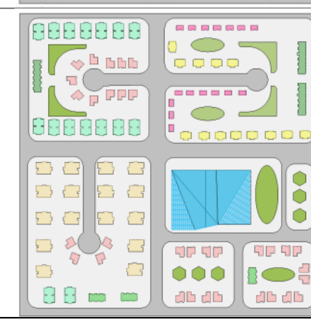


Note- SFD: Single family detached; CZ: climatic zone

Figure 6-2 Distribution of residential archetypes

The details of DMUs at neighborhood levels are described in **Table 6-2**, respectively. Here the planimetric views shows distribution of the seven archetypes in at each location. Based on results of energy, cost and GHG for residential archetypes in Chapter 5 the final indicators values for the case study at the building level from government and investor perspective are shown in **Table 6-3** and **Table 6-4**. The rebates value for each archetype varies with the location along with the associated energy savings and GHG reduction potential. The bottom-up energy modelling method provided in section 6.2.1 is used for obtaining final indicators at the neighborhood level. Here the amount of rebates, energy and GHG reduction for each archetype are multiplied by the number of houses present in neighborhood following local statistics and assumptions considered in **Table 6-2**. From these it is observed that the differences present in indicators values are not linearly increased, rather the specific neighborhood pattern will rule how much the costs and savings of individual home contribute towards the whole neighborhood performance. **Table 6-5** and **Table 6-6** show the 3 DMUs details at the neighborhood level. As an illustration of buildings impact at neighborhood level a 3D model is constructed for Thompson Okanagan (CZ-5). A color scale is also allotted to the amount of GHG reduction by each archetype. **Figure 6-3** hence enables a visualization of the neighborhood performance and can be used for comparing different neighborhoods. The overall GHG reduction potential of Thompson Okanagan is seen to be 281,547 $kgCO_2$-eq./GJ. IT should be noted that this value is obtained from application of a limited set of energy upgrades. As more renewable energy systems and more energy efficient systems are

Table 6-2 Description of DMUs at neighborhood level

No.	DMU	Description	Planimetric view
1.	Mainland/Southwest (CZ 4)	A new neighborhood consists of 100 residential buildings. The neighborhood is dominated by multi-unit residential apartments and utilized Vancouver city statistics for residential archetype distribution present in Statistics Canada 2016 [422]. There 5 Small SFD; 11 medium SFD; 5 large SFD; 28 Duplex; 2 triplex; 46 quadplex and 3 six-unit homes.	
2.	Thompson-Okanagan (CZ 5)	A new neighborhood consists of 100 residential buildings. The neighborhood is dominated by single family detached homes and utilized Kamloops city statistics for residential archetype distribution present in Statistics Canada 2016 [422]. There 17 Small SFD; 34 medium SFD; 17 large SFD; 8 Duplex; 4 triplex; 17 quadplex and 4 six-unit homes.	
7.	Northeast (CZ 6)	A new neighborhood consists of 100 residential buildings. The neighborhood is dominated by single family detached homes and utilized Prince George city statistics for residential archetype distribution present in Statistics Canada 2016 [422]. There 16 Small SFD; 33 medium SFD; 16 large SFD; 13 Duplex; 3 triplex; 16 quadplex and 3 six-unit homes.	
Key	Small SFD; Medium SFD; Large SFD; Duplex	Triplex; Quadplex; Six Unit	

Note- SFD: Single family detached; CZ: climatic zone; DMU: Decision making unit

Table 6-3 Building Level: Government Perspective

Location	DMU	Input	Output	
		Rebates (CA$)	Energy saved (kWh)	GHG reduction (tCO_2-eq.)
Mainland/Southeast (CZ 4)	DMU1	6,000	4,058.43	923.26
	DMU2	6,000	5,265.48	1,444.47
	DMU3	6,000	11,484.18	2,303.69
	DMU4	12,000	7,443.16	2,630.93
	DMU5	18,000	10,687.53	3,862.56
	DMU6	24,000	14,211.05	5,143.55
	DMU7	36,000	20,398.15	7,551.89
Thompson Okanagan (CZ 5)	DMU1	4,000	4,110.83	942.69
	DMU2	3,000	5,995.64	1,584.67
	DMU3	6,000	12,538.54	2,487.40
	DMU4	8,000	3,128.24	2,891.63
	DMU5	12,000	12,885.40	4,291.47
	DMU6	16,000	16,996.14	5,690.36
	DMU7	24,000	25,260.88	8,492.96
Northeast (CZ 6)	DMU1	0	5,354.14	1,187.93
	DMU2	0	7,643.07	1,937.25
	DMU3	6,000	15,748.88	3,104.44
	DMU4	6,000	9,096.34	3,541.48
	DMU5	9,000	16,483.21	5,246.44
	DMU6	16,000	21,612.41	6,934.37
	DMU7	18,000	32,328.13	10,381.73

Table 6-4 Building Level: Investor Perspective

Location	DMU	Input	Output	
		Difference in life cycle costs (CA$)	Energy saved (kWh)	GHG reduction (tCO_2-eq.)
Mainland/ Southeast (CZ 4)	DMU1	11,915.41	4,058.43	923.26
	DMU2	25,684.00	5,265.48	1,444.47
	DMU3	36,419.94	11,484.18	2,303.69
	DMU4	41,019.66	7,443.16	2,630.93
	DMU5	64,346.14	10,687.53	3,862.56
	DMU6	100,951.70	14,211.05	5,143.55
	DMU7	144,975.19	20,398.15	7,551.89
Thompson Okanagan (CZ 5)	DMU1	11,463.85	4,110.83	942.69
	DMU2	24,014.28	5,995.64	1,584.67
	DMU3	33,384.58	12,538.54	2,487.40
	DMU4	38,527.47	3,128.24	2,891.63
	DMU5	67,985.84	12,885.40	4,291.47
	DMU6	97,336.90	16,996.14	5,690.36
	DMU7	139,280.98	25,260.88	8,492.96
Northeast (CZ 6)	DMU1	11,002.30	5,354.14	1,187.93
	DMU2	23,733.67	7,643.07	1,937.25
	DMU3	31,615.77	15,748.88	3,104.44
	DMU4	38,815.31	9,096.34	3,541.48
	DMU5	63,504.19	16,483.21	5,246.44
	DMU6	99,757.38	21,612.41	6,934.37
	DMU7	142,712.34	32,328.13	10,381.73

Note- CZ: climatic zone; DMU: Decision making unit

Table 6-5 Neighborhood Level: Governments' Perspective

DMU	Input	Output	
	Rebates (CA$)	Energy saved (kWh)	GHG reduction (tCO_2-eq.)
DMU1	1,710,000	1,081,572.60	372,758.44
DMU2	748,000	946,276.27	281,547.41
DMU3	512,500	1,201,808.63	336,585.24

Note- DMU: Decision making unit

Table 6-6 Neighborhood Level: Investor Perspective

DMU	Input	Output	
	Difference in life cycle costs (CA$)	Energy saved (kWh)	GHG reduction (tCO_2-eq.)
DMU1	6,879,389.00	1,081,572.60	372,758.44
DMU2	4,347,703.78	946,276.27	281,547.41
DMU3	4,183,254.40	1,201,808.63	336,585.24

Note- DMU: Decision making unit

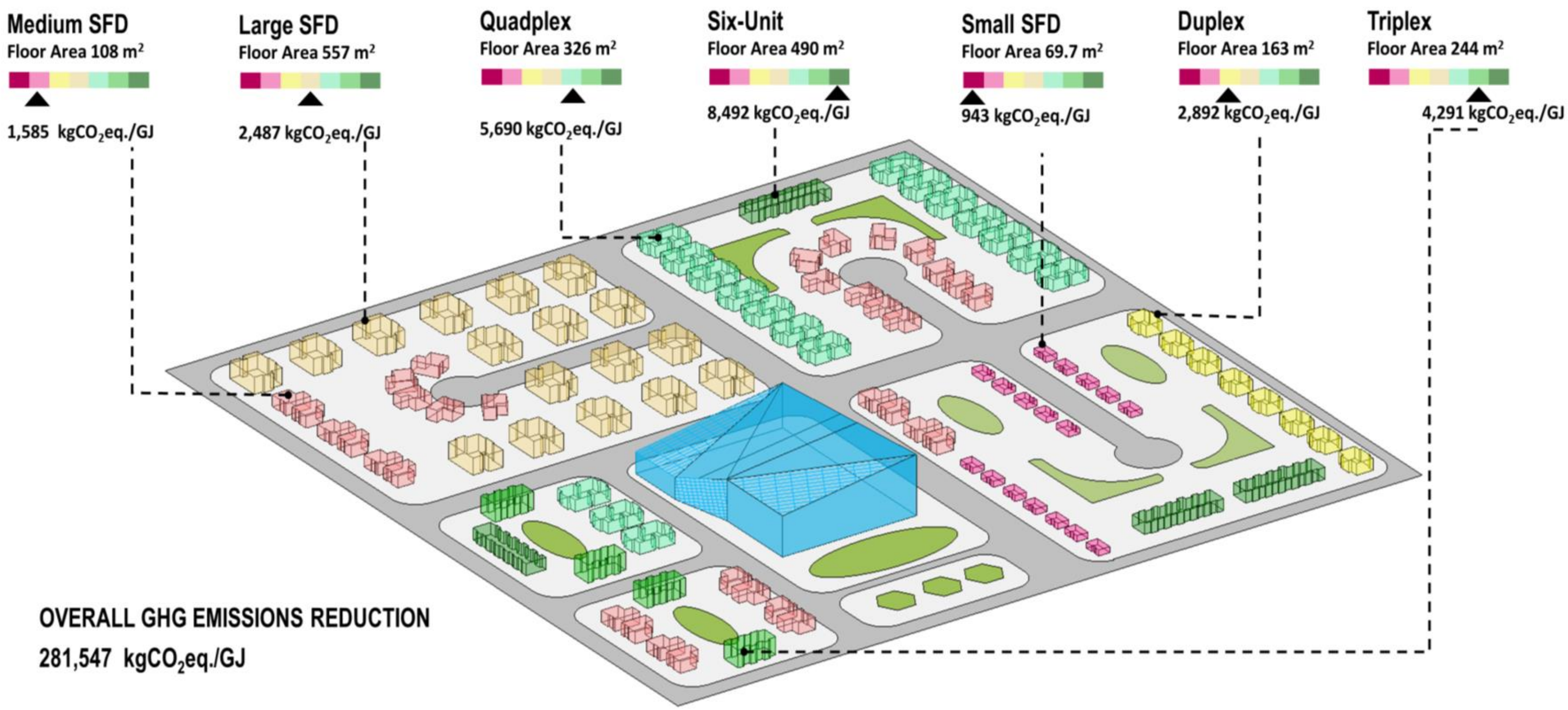
adopted this value of overall GHG emissions reductions would be much higher. Likewise, when a different neighborhood layout is considered this value will change.

6.4 Results and Discussion

This section presents the results obtained from two points of view at two levels: the individual residential archetype at the building level and efficiency at the neighborhood level.

6.4.1 Building Level

The results of efficiency at the building level from the investors' point of view can help establish a performance benchmark and help in comparing investment potential in different residential archetypes. The results from the government perspective inform about the best-performing archetypes where the subsidy funds allocation will yield maximum benefits. The building level efficiency from the government perspective at the building level is shown in **Table 6-7**. It is seen that the efficiency rankings change with location. For the milder climate of Mainland/Southwest, the rebates are efficient for large SFD. In-efficient archetypes in Mainland/Southwest show values from 0.627 to 0.4008. The results indicate that small SFD is the most in-efficient from a government perspective, while attached homes investigated show similar values. Thus government subsidies allocated to single-family detached homes will give the highest benefits.



Note- SFD: Single family detached home; CZ: climatic zone; GHG: greenhouse gases

Figure 6-3 GHG Emission reduction at neighborhood level for Thompson Okanagan (CZ-5)

Archetypes in the Thompson Okanagan show a similar ranking to archetypes in the Mainland/Southwest; however, the in-efficient units in this region behave better to rebates compared to the milder climate and their efficiency values range from 0.6843 to 0.5023. In addition, the Thompson Okanagan contains two efficient archetypes: Medium SFD and Large SFD. In contrast to the Mainland/Southwest and the Thompson Okanagan, the archetypes in the Northeast show an overall poor performance. The most efficient archetype is Medium SFD, while the range of inefficient DMUs ranges from 0.7005 to 0.0018. Overall, attached homes show the lowest efficiency under current rebates.

Table 6-7 Building Level: Rebates efficiency Government Perspective

DMU	Mainland/Southwest (CZ4)		Thompson Okanagan (CZ 5)		Northeast (CZ 6)	
	Efficiency	Rank	Efficiency	Rank	Efficiency	Rank
DMU1	0.4008	7	0.5023	6	0.7005	2
DMU2	0.627	2	1	**1**	1	**1**
DMU3	1	**1**	1	**1**	0.0021	6
DMU4	0.571	3	0.6843	2	0.0018	7
DMU5	0.5589	4	0.677	3	0.0027	5
DMU6	0.5582	5	0.6733	4	0.0036	4
DMU7	0.5464	6	0.6699	5	0.0053	3

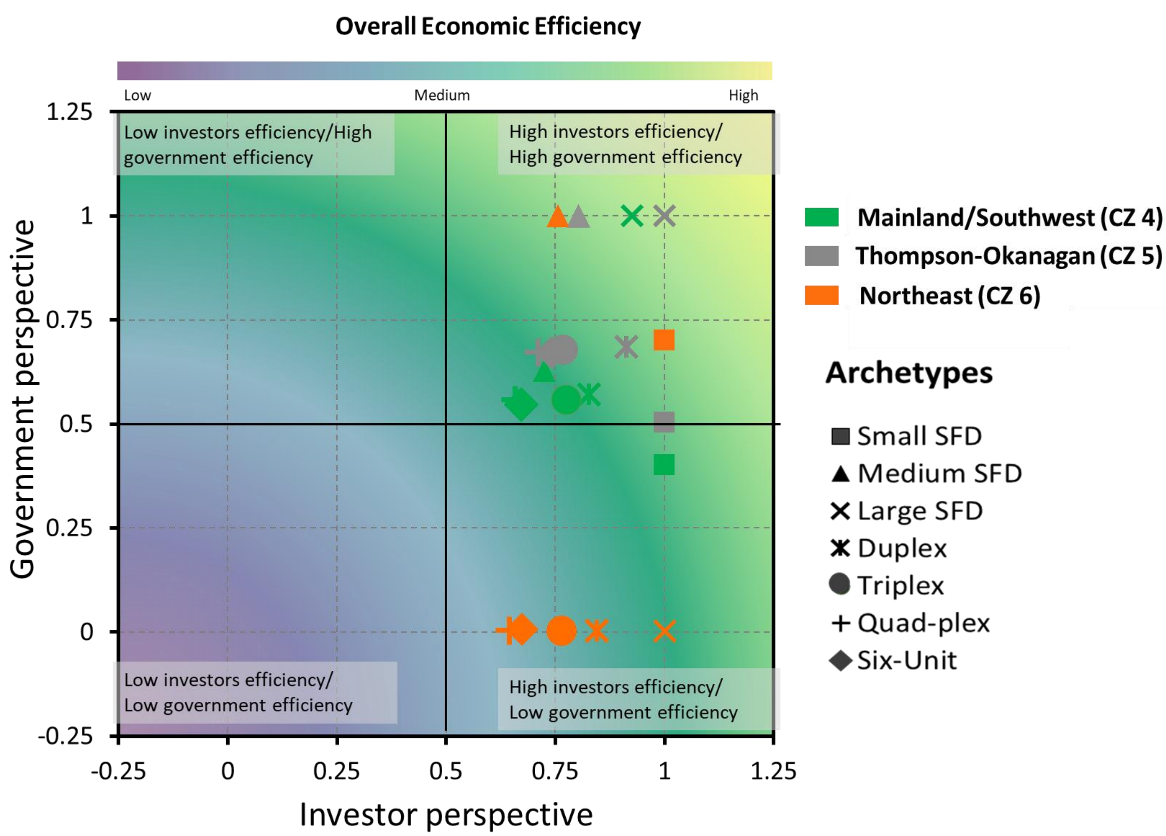
The building level efficiency from investors' perspective at the building level is shown in **Table 6-8**. Similar to government rebates efficiency, the rankings for investment vary with location. In contrast to government rebates, the efficiencies from investors' perspective are better and do not show high variation. In this respect, Small SFD is the most efficient unit for investment in all three locations. For the Mainland/Southwest, efficiency values range from 0.9258 to 0.6576. In the Thompson Okanagan and the Northeast, in addition to Small SFD, the investment in Large SFD is also efficient. The inefficient units range from 0.9127 to 0.7109 and 0.845 to 0.6438 for the Thompson Okanagan and the Northeast, respectively. Investors' perspective also indicates that investment in single-detached homes is a more efficient option compared to attached homes. Overall results indicate that investment in almost all homes of the Thompson Okanagan will be beneficial for investors.

Figure 6-4 shows a comparison of efficiencies between the two perspectives for the tested regions and the seven archetypes used as DMUs. The quadrant chart enables the comparison of the DMUs in a straightforward manner. It is seen that all DMUs fall in the higher investors' efficiency quadrant; however, for the more extreme colder climate of the Northeast, most homes are inefficient from a government perspective.

Table 6-8 Building Level: Investment efficiency Investor Perspective

DMU	Mainland/Southwest (CZ4)		Thompson Okanagan (CZ 5)		Northeast (CZ 6)	
	Efficiency	Rank	Efficiency	Rank	Efficiency	Rank
DMU1	1	**1**	1	**1**	1	**1**
DMU2	0.7258	5	0.8025	3	0.756	4
DMU3	0.9258	2	1	**1**	1	**1**
DMU4	0.8278	3	0.9127	2	0.845	2
DMU5	0.7747	4	0.7676	4	0.7652	3
DMU6	0.6576	7	0.7109	6	0.6438	6
DMU7	0.6723	6	0.7415	5	0.6738	5

Note- CZ: climatic zone; DMU: Decision making unit



Note- SFD: single family detached home

Figure 6-4 Economic Efficiency from investors and government perspective at the building level

6.4.2 Neighborhood Level

The results for efficiencies at the neighborhood level from both investors and government perspectives are shown in **Figure 6-5**. It is seen that both from government and investors perspectives, investment in neighborhoods located in the Northeast is most efficient. This is in contrast to the results obtained for the building level. This change is observed because of how the archetypes are actually distributed among the three regions.

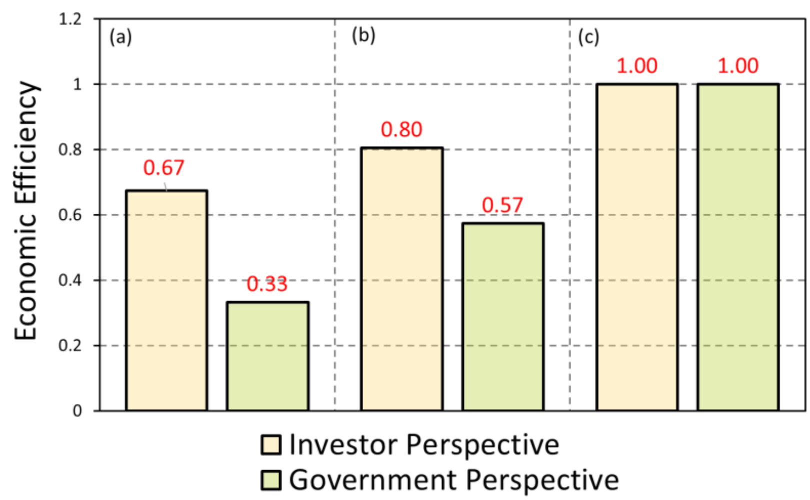


Figure 6-5 Economic Efficiency from investors and government perspective at the neighborhood level: (a) Mainland/Southwest (CZ 4), (b) Thompson-Okanagan (CZ 5) and (c) Northeast (CZ 6)

The Mainland/Southwest is dominated by attached homes that had lower efficiencies compared to detached homes, while more efficient detached homes dominate the Northeast. In addition, the cost factors play an important role, the costs are higher for the same energy performance upgrades in the Mainland/Southwest and Thompson Okanagan as compared to those in the Northeast climate. It is also observed that government and investor efficiencies are better for the Thompson Okanagan (0.80 and 0.57) compared to the Mainland/Southwest (0.67 and 0.33). Similar to results at the building level, the investors' perspective has better efficiencies compared to the government perspective. These results indicate that under current rebates the government can obtain maximum benefits by directing maximum rebates towards Northeast neighborhoods. Investors' perspective can help benchmark neighborhoods' performance and direct future investors to obtain more sustainable neighborhoods.

6.4.3 Limitations and future direction

The same set of limitations related to the residential archetypes, limited set EPUs, locations and economic conditions that govern chapter 5, section 5.4.5 should also be considered for determining DMUs at individual building and neighborhood levels. As preliminary research on rebates efficiency, the DEA method using CCR-output based model proves a good approach. However, CCR-output based models have low discriminating ability and give more weight to favorable inputs and outputs than unavoidable ones, resulting in overestimating results [456]. Future research on rebates efficiency should consider using more advanced DEA models, such as cross-efficiency, to help address these shortcomings. Another direction for future research is conducting a sensitivity analysis that can highlight the main factors making a residential archetype or neighborhood more efficient than others. A robustness test can also be performed by removing one input or output and running DEA models and comparing the results [457]. In addition, a similar layout of neighborhood was considered for three locations. In reality, the neighborhoods layout varies even in the same city. Therefore, more comprehensive studies with various possible neighborhood layouts need to be explored and compared for rebates performance. This will help improve existing and new neighborhoods.

6.5 Summary

Chapter 6 investigated the efficiencies of existing rebates and investments from government and investors perspectives at the building and neighborhood level through the application of the CCR-output based model. The feasibility of the methodology is demonstrated through an application on rebates offered for a recently upgraded building energy code in British Columbia, Canada.

The results provide insights into the impacts of current rebates offered for meeting targets of the recently upgraded building energy code in British Columbia, Canada. It is observed under the current rebates at the building level, the rebates directed towards Large SFD and Medium SFD will have the highest efficiency. At the neighborhood level, the most economically sound investment by government and investors are for archetypes located in the Northeast. It should be noted that the research was limited to only three locations, climate zones and seven archetypes. It is possible that other archetypes and neighborhoods are more efficient than the tested samples. CCR-output based model used for this methodology can provide relative efficiencies and is sufficient for the current investigation. More advanced models are present for the reallocation of subsidies that can be used for future research.

Overall, the results obtained from this research can help the regional government is allocating subsidies to archetypes while the efficiency of investments can help end-users make informed decisions regarding their future expenditure. At neighborhood levels the efficiency values can help in the distribution of national and provincial subsidies. Likewise, the investment efficiency at neighborhood level can help in benchmarking and comparing regions and indicate what changes need to be incorporated for improvement in performance.

Chapter 7 Operation strategy selection of a Public Building: Decision making with life cycle thinking approach

Parts of this chapter have been published in Elsevier's *Journal of Cleaner Production*, as an article titled "A process-based LCA for selection of low-impact DBPs control strategy for indoor swimming pool operation"[458].

7.1 Background

Financial Incentives (FIs) are assigned according to the level of energy savings targets achieved. However, buildings' energy use changes with the building operation schedule and can result in higher energy savings and hence eligible incentives [40]. FIs for achieving energy efficient buildings can either yield a positive impact on human health, such as introducing incentives on wood pellets instead of conventional coal stoves or using renewable energy sources. In other cases, reducing building energy use can overlook the indoor environmental problems leading to a negative impact on building occupants [43]. Likewise, if importance is given to reducing the impacts on human health, the eligible incentives will be reduced. This chapter explores the implication of building operating conditions on FIs eligibility criteria. The chapter uses a public aquatic centre building as a case study to demonstrate the problem, methodology and solution.

Swimming is an important recreational activity suitable for all age groups with varying physical abilities [459]. The World Health Organization recommends swimming for health benefits, mental relaxation and social interaction [460]. Indoor swimming is often preferred over outdoor swimming by the population living in cold regions as it offers a comfortable swimming environment throughout the year. Hence, the number of indoor swimming pools (ISPs) exceeds outdoor swimming pools in many countries. A similar trend is observed in Canada, where ISPs account for 75% of the total 3,615 public pools [461].

Maintaining good water quality in swimming pools is of great importance to protecting the health of swimmers and non-swimmers [462]. Swimming pool water can be a host to various harmful microorganisms, such as bacteria, viruses and algae, which could pose risks to bathers' health. Disinfectants are added to swimming pool water to control the population of microorganisms

[463]. Chlorine is the most common disinfectant applied to swimming pools due to its low cost and high effectiveness in deactivating microorganisms [464]. However, chlorine can react with anthropogenic organic matter (e.g., human sweat, saliva, personal care products) in swimming pool water to form disinfection by-products (DBPs), such as trihalomethanes (THMs) and haloacetic acids (HAAs) [465,466]. Excessive exposure to DBPs can cause harm to the health of bathers and employees who spent considerable time in ISPs [467]. DBPs may affect human health through dermal contact, accidental oral intake and inhalation pathways [468–470]. Extensive research has identified links between DBPs exposure and various human health effects ranging from respiratory irritation to different cancers [471–474]. Hence, it is essential to develop and implement DBPs control strategies in ISPs to protect bathers and ISP staff's health.

DBPs control strategies can be developed by changing swimmer’s behavior and/or the operating conditions of engineering systems that remove or reduce DBPs and their precursors in the ISP environment [459]. On the other hand, implementation of a DBPs control strategy will alter the energy and resource consumption of the existing pool operation. A large quantity of energy, water, chemical and other resources are required in ISP operation, resulting in significant environmental impacts. ISPs also have a long operating or service life; for example, a typical ISP is expected to have a service lifespan of 40–75 years [475]. Hence, considerable environmental impacts can be generated with the application of DBPs control strategies throughout the long service life of an ISP. To the best of the authors’ knowledge, limited studies have investigated the environmental impacts of DBPs control strategies in ISP operation. ISPs are important energy consumers and contributors to global warming. Thus, it is important to assess the lifecycle impact of DBPs control strategies and select suitable strategies that can achieve promising DBPs control performance with minimum resource consumption.

7.1.1 DBPs Control Strategies

Human health risks due to DBPs exposure can be mitigated through the adoption of appropriate control strategies. Development of a specific DBPs control strategy is based on a number of ISP design and management factors including, pool types (e.g., leisure pools, lap pools, hot tubs) [476,477], source water quality (e.g., organic and inorganic precursors, pH, temperature) [465,478–481], disinfection processes (methods) (e.g., UV treatment, chlorination, ozonation)

[482–484], bathers (e.g., number, behavior and personal hygiene condition) [477,485,486] and air ventilation conditions [487,488]. DBPs control strategies are developed based on a modification of existing engineering systems as well as users' behaviors [459,489]. These strategies can be divided into three main categories: precursors removal, modification of water treatment processes and removal of DBPs from the pool environment [490,491]. The selection of an effective DBPs control strategy depends upon the specific pool conditions, bathers' behaviors, engineering systems, resource availability and preference and facility managers' expertise.

The formation of DBPs in pools occurs at a high rate; hence some researchers recommend that DBPs control strategies should focus on the removal of anthropogenic organic precursors [462]. The reduction of precursors can be achieved by changing bathers' behaviors such as pre-swim showering and wearing proper bathing caps and swimsuits [492]. DBPs precursors can also be reduced by keeping the pH of water at a relatively low level and reducing water age (retention time) by increasing turnover rates [493]. Improving the water treatment process is another important strategy that involves modification and/or combination of existing disinfection methods; such as a combination of enhanced coagulation with filtration [493,494]. Disinfection methods include chlorination, electrochemically generated/mixed oxidants, UV- treatment, use of hydrogen peroxide, ozonation and their combinations [493,495]. Once formed, DBPs can be present in the pool water and air of an ISP. DBPs removal from water involves membrane filtration, advanced oxidation, thermal and chemical reduction [495]; while their removal from the air can be achieved by changing the operation of heating and ventilation systems and controlling surface air flows through exhaust fans [459,496]. The three categories may be implemented individually or in combinations for effective DBPs control. Different strategies are associated with varied energy, water and chemical use during the long pool service life and therefore, investigating their lifecycle environmental impacts is necessary.

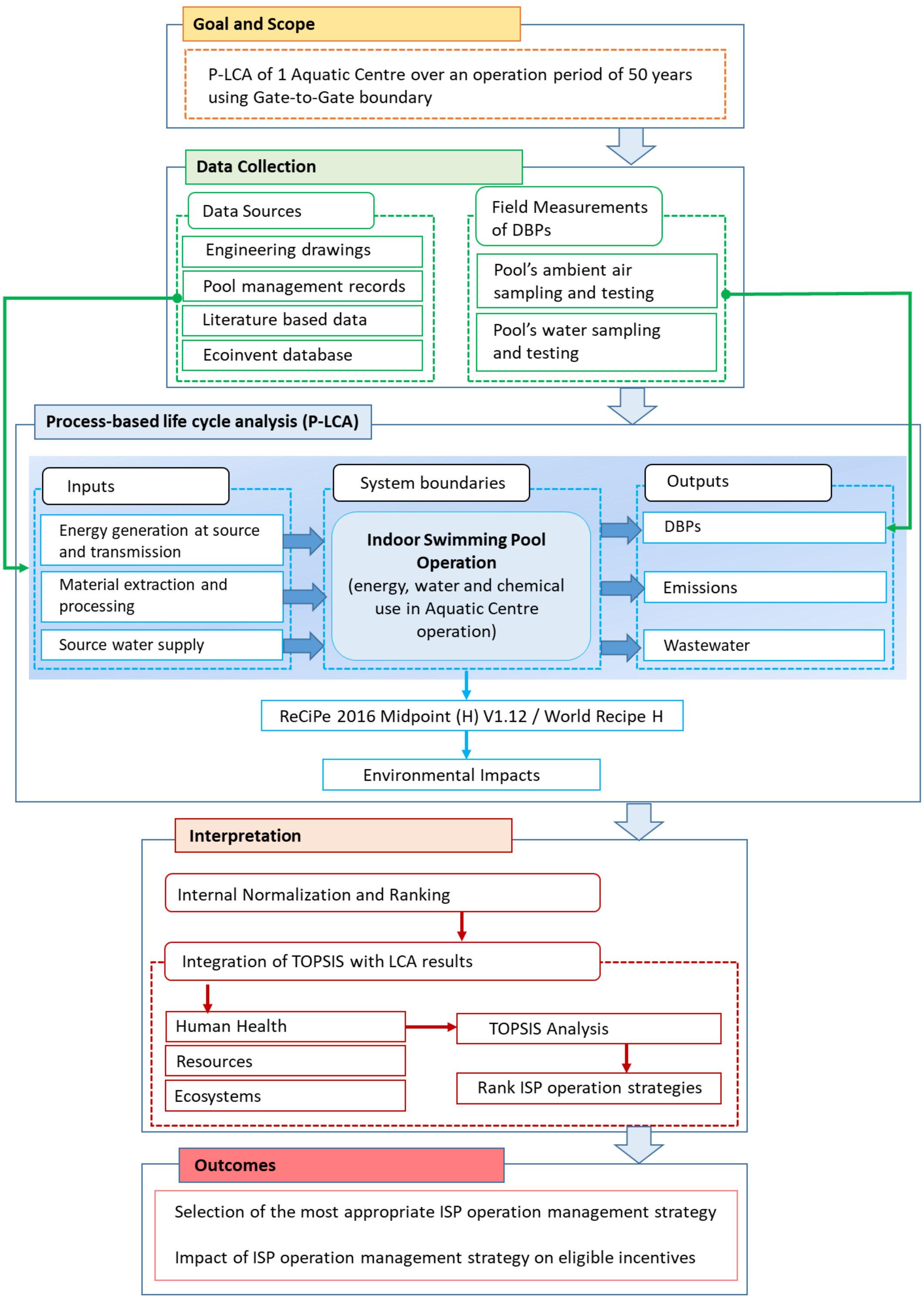
7.1.2 Process-based LCA

Life cycle assessment (LCA) is a standard procedure to evaluate the environmental performance of various processes and man-made products, from raw materials acquisition through operation and maintenance to the ultimate waste disposal [497]. LCA can be performed using three methods: (1) process-based (P-LCA), (2) input-output-based (IO-LCA) and (3) hybrid LCA. P-LCA calculates environmental impacts due to inputs and potential outputs of processes in each life-cycle phase [498]. It can assess the impact of a series of processes on consequential outcomes and is considered to provide highly accurate results. In comparison, IO-LCA is a top-down approach that uses sector-level data based on the economy to generate inventories. Though IO-LCA considers all processes, data from its inventories are not detailed enough to conduct a comprehensive assessment to reach decisions at the product/process level [499]. Hybrid-LCA involves the combination of P-LCA and IO-LCA methods and has the advantages of both methods. However, Yang et al. [500] found that hybrid-LCA does not always give more accurate results than P-LCA. P-LCA is known to provide more accurate results than IO-LCA [499]. P-LCA is a part of ISO standard guidelines [501]. The system boundary of P-LCA is based on the goal and scope of a study; hence, the data inventory is based on the processes within system boundaries [502]. Cut-off and truncation errors are a common limitation of any P-LCA [503,504]. Therefore, cut-off criteria should be selected carefully to minimize errors and obtain realistic environmental impacts.

Although several studies have explored the energy use [505–509], water use [505,510] and chemical emissions [470,511] in ISP operations, the lifecycle environmental impact of ISP operation is still not well understood. Forrest & Williams [512] developed a hybrid-LCA model to determine the carbon footprint of private residential pools in the United States. However, the study was limited to private outdoor residential pools associated with significantly different energy and resource consumption compared to ISPs. Furthermore, the study only investigated carbon emissions but did not explore other environmental impacts such as ozone depletion or human toxicity. In short, a significant knowledge gap exists in the LCA of public ISPs.

7.2 Methodology

A P-LCA methodology is developed to help select DBPs control strategies with promising DBPs control performance and low environmental impacts. The processes and products of each DBPs control strategy are considered, including energy, water and chemical use as well as emissions of contaminants. The proposed methodology consists of four main phases, as shown in **Figure 7-1**.



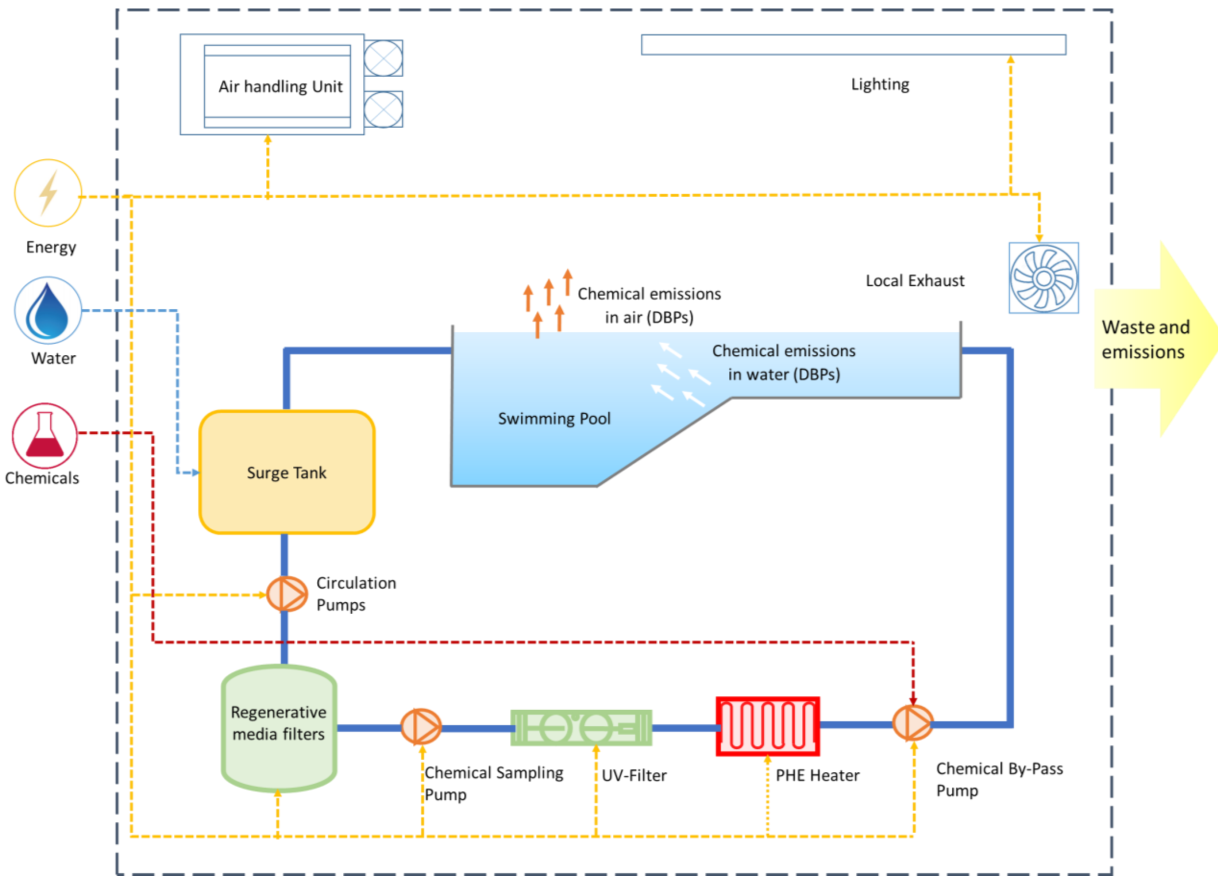
Note- ISP: indoor swimming pool; TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution; DBPs: Disinfection byproducts; LCA: Life cycle assessment; P-LCA: process based LCA

Figure 7-1 Proposed P-LCA methodology for selecting low impact DBPs control strategy

7.2.1 Goal and Scope

According to ISO 14044 [513], the temporal and spatial boundaries of the system being assessed should be defined in accordance with the goal of the study. The goal in this phase of the study was to evaluate DBPs control strategies applied to engineering systems in ISP and determine the strategy with the lowest environmental impacts by using P-LCA. DBPs emitted in pools are a known human health risk, however the determination of the direct human health impacts is outside the scope of this methodology. Cradle-to-gate boundary is considered for determining the environmental impacts of different processes of DBPs control strategies. The functional unit was defined as operating a DBPs control strategy in a standard ISP facility to ensure low DBPs emissions in air and water over 50 years. The standard ISP has four pools, including a 50-m pool, a 20-m pool, a leisure pool and a hot tub and the total pool surface area is around 3100 m^2. This time period is selected as most commercial buildings have a service life of 50 years [514,515]. Statistics Canada [461] has reported that pools with a length $\geq$ 50 m are expected to have a service life of 48 years, while pools with a length $\leq$ 25 m have an expected service life of 38 years. Therefore, a temporal boundary of 50 years is considered appropriate for determining the lifecycle environmental impacts of public ISPs. Permissible levels of DBPs emissions, defined by air and water quality guidelines, are another important criterion in the selection of DBPs control strategies. For example, a few countries have implemented DBPs emission levels (between 20-100μg/L) for swimming pool waters [516–518]. However, there is no available DBP concentration guideline for swimming pool water in Canada. Thus, the DBP concentration guidelines were not considered in defining the functional unit in this study. The system boundaries for the P-LCA are provided in **Figure 7-2**.

Since this study's goal was to assess the environmental impacts associated with DBPs control strategies, only processes involved in ISP operation within the pool environment are included in the system boundaries. DBPs control strategies are applied during the operation stage of ISP. Hence, other life cycle phases such as extraction of materials, transportation, construction and end of life stages are excluded from system boundaries. Similarly, DBPs control strategies do not alter the infrastructure of the ISP, so the environmental impacts associated with the pool infrastructure and systems, such as routine maintenance and replacement of swimming pool materials and systems, building envelope not part of the P-LCA study. Hence, the terms ISP operation and DBPs control strategies can be used interchangeably in this study as they represent the same meaning.



Note- DBPs: Disinfection byproducts; UV: ultraviolet treatment; PHE: plate heat exchanger

Figure 7-2 System boundaries for P-LCA of DBPs control strategy

7.2.2 Data Collection

Energy, water and chemical use data in ISP operations can be obtained from a variety of sources, including calculations based on the engineering drawings, pool operation records, expert judgments, existing literature and databases. Ecoinvent 3 is the world's largest and most transparent database on unit processes and is extensively used in different LCAs [519]; hence, Ecoinvent 3 database is appropriate for generating life cycle inventory (LCI) for ISP operation. Three main flows: energy, water and chemicals, are considered in the LCI. Scenario analysis is the most commonly used method for the comparison of environmental impacts under varying operating conditions [520]. Therefore, the scenario analysis was used for investigating the environmental impacts as a result of implementing different ISP operation management strategies that include a combination of energy-reducing strategies and DBPs control strategies. The operating condition of an ISP without implementing any DBPs control strategy represented the baseline condition. DBPs control strategies applicable to a specific ISP need to be explored and their impacts will be determined using scenario-based assessments.

The LCI is generated based on the collected operational data and the measured DBPs concentrations in the ISP environment. As shown in **Figure 7-3**, the ISP operational data, as inputs to the methodology, include disinfectants and water softeners added to water, energy used by heating, ventilation and air conditioning (HVAC) systems, water consumption and generation of DBPs and wastewater.

Transmissions of energy and water from the nearest available source present in the Ecoinvent 3 database are used. Energy use under a specific DBPs control strategy depends on the number of bathers present in pools, type of pool, water heating system (e.g. water heat pumps, heat heaters, etc.), water treatment systems (e.g. UV treatment, filtration, ozonation etc.), on and off schedules of pools' water features (e.g., water sprayers, water wheel), chemical pumps in operation and the setting of water and air circulation systems. The proposed methodology focuses on the operation of swimming pools alone. Thus the energy uses in other ISP amenities, such as exercise rooms and washrooms, is not evaluated. **Table 7-1** shows models and tools used for determining energy use in ISP operations. The total energy used for swimming pool operation can be expressed as a combination of energy consumption of operating different systems/components in an ISP, such as the energy used for water heating, pump operation, rainwater harvesting system (if applicable), HVAC system, lighting system and water treatment.

The energy used to heat water in swimming pools is evaluated through the Enerpool tool which is specifically designed for swimming pools in Canada [521]. A variety of pumps are used in swimming pools that include chemical, chlorination, pH adjustment, circulation and by-pass pumps. The flow rate and pressure head are used to determine the amount of energy used by each pump. Energy used by rainwater harvesting systems (RWH) ranges from 0.19-5.51 kWh/m^3,

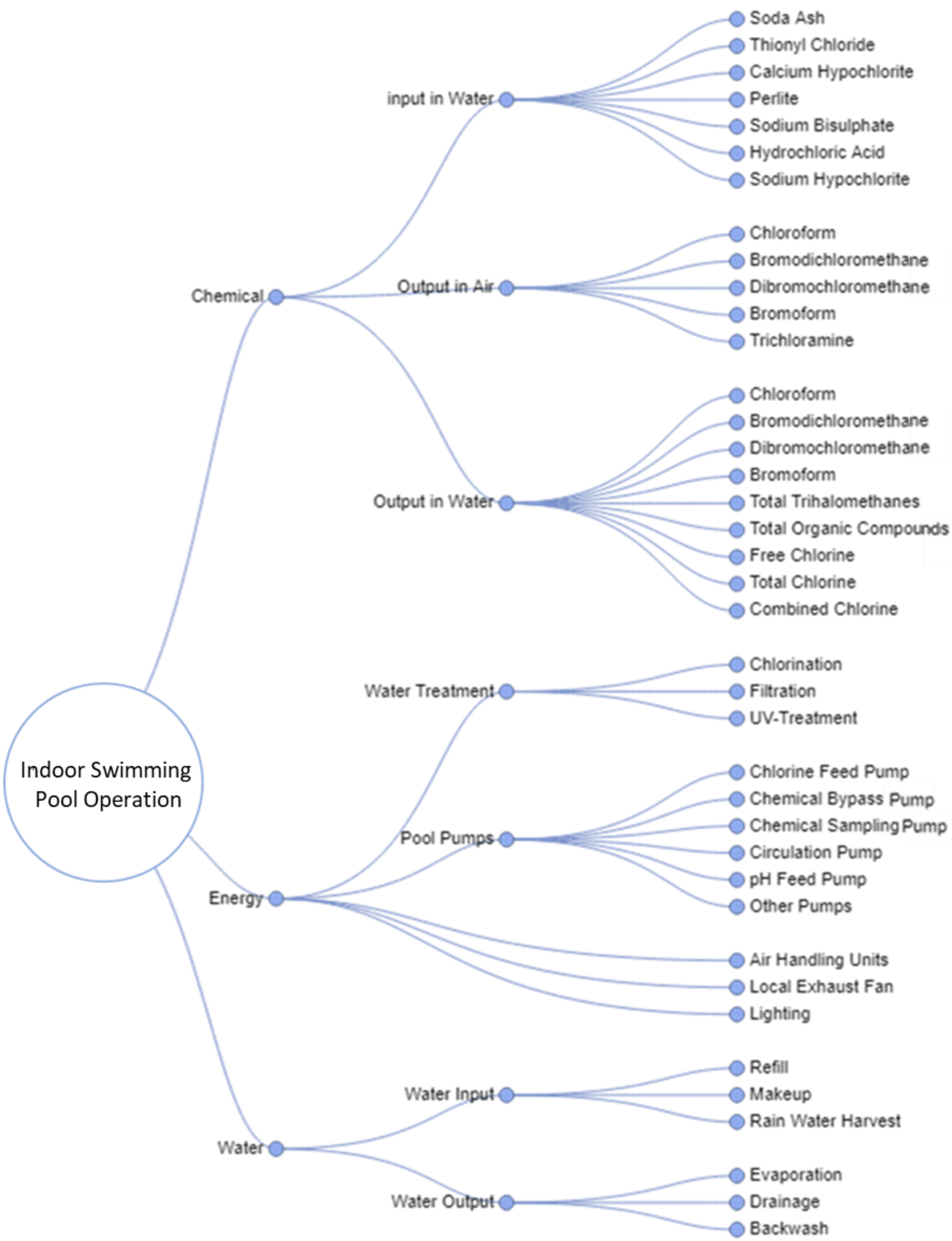


Figure 7-3 Input and output parameters for DBPs control strategy

Table 7-1 Background information for energy calculations

Energy use	Model Used/Source	Description	Ref.
Pool heating	Enerpool Tool 3.0	Enerpool Tool is a program developed by NRCan Canada. This program is capable of calculating heating energy required for swimming pools of different types located in Canada and US cities.	[521]
Pool pumps	$E = \left(\frac{F_r * H}{3196}\right)$ Where: E=Energy used by pump (kW) F_r=Flow rate (m^3/day) H=Total head (m)	Energy consumed by the pumps used for refilling pools depends upon the pump design and the flow rate of water.	[522]
RWH	0.19-5.51 kWh/m^3	Energy consumed by rain water harvesting system depends upon the water storing capacity.	[523]
HVAC	Energy Calculator	Energy Calculator is an online energy tool that can calculate the energy used by air handling units by the provision of operating design parameters of HVAC units.	[524]
Local exhaust vent	$E = (F_r * P * t)$ Where: E = Energy use by local exhaust vent (kWh) F_r=Flow rate P= Local exhaust power (W) t= Operating time (Hours)	Local exhaust vents help in the removal of DBPs on the pool surface and are needed because the majority of the DBPs emitted in the air from the pools are present near the surface of the water	[525]
Lighting	$E = (\mathrm{P} * \Delta t)$ Where: E = Energy use per luminaire (kWh) P = Luminaire power (W) Δt = Full load hours per luminaire (hrs)	Energy consumed by the lighting present in the indoor swimming pool facility.	[526]
UV-treatment	$E = (0.0145 * Q)$ Where: E = Energy use (kWh) Q = Water flow rate (m^3/day)	Ultraviolet (UV)- treatment is used for removing chlorine-resistant pathogens in swimming pool water. The energy consumed through UV treatment depends upon the intensity of UV system to destroy pathogens. Compared to other water treatment systems UV-treatment is more energy-intensive.	[527,528]
Chlorination	$E = 0.0021 * Q$ Where: E = Energy use (kWh) Q = Water flow rate (m^3/day)	Chlorination is the most common disinfection method with fast and long-lasting effects. Energy used in chlorination depends upon the water flow rate in a swimming pool.	[529]
Filtration	$E = (0.1717 * Q)$ Where: E = Energy use (KWh) Q = Water flow rate (m^3/day)	Energy used in filtration depends upon the flow rate of swimming pool water filtered.	[527]

depending on the system's size and type [523]. Energy used by HVAC systems mainly depends on the number of air handling units (AHU), type of exhaust system in use and their operational conditions. Lighting energy is determined by the operation schedules as well as the types and number of lighting fixtures in an ISP. Energy used by UV-treatment, chlorination and filtration depends on the water circulation rate within pools and hence varies with the size and type of pools.

The water data for LCI can be calculated using a water balance model similar to the model by Gallion et al. [530]. The water balance model is provided:

$$W_{total} = \sum W_i - \sum W_j \qquad \textit{Equation 7-1}$$

where W_{total} is the total water use, W_i represents the replenished water and W_j represents the water

loss due to backwash, evaporation and drainage. The specific models used for evaluating water replenishment and loss are provided in **Table 7-2.** The amount of water refilled depends on the number of swimmers, size of the pool and maintenance

frequency. Water provided by RWH depends on the system capacity and local weather and topography conditions. It should be noted that RWH is not a commonly used feature in ISPs and the value will become zero if RWH is not used for a pool water refill. Evaporation is not only a significant contributor to the total water loss but also to energy use because extra energy is required to heat the pool water refilled [531]. The evaporation model developed by Shah [532] is the most commonly used for determining the evaporation of swimming pool water. This model describes the correlations of water, air and energy use in swimming pools based on the experimental data. Shah’s model [532] calculates water evaporation in both occupied and unoccupied pools and is used to generate water use data in the LCI. The amount of water drained also varies with the maintenance frequency and volume of pools. Water used for cleaning filters and pools through backwashing depends on the flow rate of backwashing pumps as well as the duration and frequency of backwashing [512].

Chemical use data varies from one ISP facility to another and should be collected through consultation with facility managers and operators. The concentrations of DBPs generated in pool

Table 7-2 Models used for water calculations

Water use	Model/Source Used	Ref.
Pool refills: Pools are refilled either to maintain water level due to spilling and evaporation or after the pool has been completely drained for maintenance and cleaning purpose.	$$P_{refill} = (V_{pool} * F_{refill})$$ Where: P_{refill}= Volume of water refilled in pool (m^3) V_{pool}= Volume of pool (m^3) F_{refill}= Refill frequency	[512]
Rainwater harvesting system: Depends on the rain water system present in the facility	P_{RWH}=Capacity of rainwater harvesting system (m^3)	[533]
Evaporation: Evaporation models consider the principle of natural convection occurring due to temperature and density differences between air on the pool surface and room air, number of swimmers and air circulation due to ventilation systems. Where: b = 0.00005 in SI units and 0.0346 in I-P units C = 35 in SI units and 290 in I-P units E=Evaporation from occupied pool E_o=Evaporation from unoccupied pool ρ_r = Density ratio of air at room conditions ρ_w = Density ratio of air at the water surface N=Number of occupants per unit pool area W_r= Humidity ratio of air at room conditions W_w= Humidity ratio of air at the water surface	Evaporation from unoccupied pools is larger of Eq.1. and Eq. 2. $E_o = C * \rho_w(\rho_w - \rho_r)^{1/3} (W_w - W_r)$ (Eq. 1) $E_o = b * (\rho_w - \rho_r)$ (Eq. 2) Evaporation from occupied pools if $N \geq 0.05$ $E/E_o = 1.9 - 21(\rho_r - \rho_w) + 5.3N$ (Eq. 3) Evaporation from occupied pools if $N<0.05$ E ranges between 0.05 and 1	[534]
Water drainage: Water drainage is required for maintenance and cleaning of the swimming pools. The frequency of drainage depends upon the size and usage of pools Example: 50-m pool is usually drained annually while leisure pools /children pools can be drained monthly.	$$P_{drain} = (V_{pool} * F)$$ Where: P_{drain}= Volume of water drained from pool (m^3) V_{pool} = Volume of pool (m^3) F = Frequency of drainage	[535]
Backwashing: Over time, the filters of the pools are clogged and regular backwashing is performed to maintain water quality of the swimming pool.	$$P_{back} = (Q_{pump} * T_{bw} * F_{bw})$$ Where: P_{back}= Volume of water used in backwashing (m^3) Q_{pump} =Pump flow rate (m^3/day) T_{bw}=Duration of backwash (hrs) F_{bw}=Frequency of backwashing	[512]

water and released to ambient air are affected by the chemical use, disinfection methods and the specific uses of the ISP facility. While chemical input data can be obtained from the annual ISP operation records, the chemical emission data can be determined by analysis of air and water samples collected from specific ISPs. It should be noted that the accuracy of P-LCA results is affected by the number of DBPs investigated. Trihalomethanes (THMs) and chloramine groups are the most prevalent DBPs in swimming pool water [469,480]. The concentrations of THMs are regulated in water quality guidelines for swimming pools in some countries [495]. THMs consist of chloroform, bromodichloromethane, dibromochloromethane and bromoform [464,536]. Both THMs and chloramine groups are considered chemical emissions in the proposed methodology.

7.2.3 Life Cycle Impact Assessment (LCIA)

The potential environmental impacts are quantified based on the inventory data [513]. The LCA methods can be categorized as problem-oriented (midpoints) and damage-oriented (endpoints) depending on the objectives. The midpoint impact assessment determines the potential impacts on the environment [537], while the endpoint assessment evaluates the impacts to the public in a specific area [538]. Since the objective of this study is to assist ISP facility managers in selecting a low-impact operation strategy midpoint impact assessment is used in the methodology. ReCipe is the most commonly used method for midpoint assessment. Midpoint impacts in ReCipe can be determined from three perspectives: individualist (I), hierarchist (H) and egalitarian (E). ReCipe (I) determines midpoint impacts over a short duration and is representative of a positive mindset; ReCipe (H) is considered to be the default scenario where midpoint impacts are quantified for a 100-year period; and ReCipe (E) represents midpoint impacts over a long duration (example 1000 years for climate change) and follows a precautionary thinking including impacts that have not been fully established [539,540]. ReCipe (H) is used in the methodology based on the consideration of the temporal boundaries of the LCA. For this study, ReCiPe 2016 Midpoint (H) V1.12 / World Recipe H in SimaPRo tool was used.

7.2.4 Interpretation

The final step of this methodology is results interpretation, which involves analysis of assessment outcomes to evaluate robustness and sensitivity of the inventory [541]. In this step, conclusions are also drawn with reference to the LCA's goals and objectives [542]. Interpretation consists of three main parts: (i) identification of significant issues in the results obtained from the LCI and impact assessment phases; (ii) validation of results by testing the study for completeness, consistency and sensitivity and (iii) drawing the conclusion, limitations and recommendations [543]. Interpretation of P-LCA results is performed in two stages: (i) using normalization to compare DBPs control strategies based on environmental impacts and (ii) using the TOPSIS method to compare DBPs control strategies using environmental impacts and DBPs emissions.

<u>Stage 1-Interpretation:</u> The results from an impact assessment are commonly normalized for interpretation. Normalization of impacts can be done either through internal or external normalization methods. Internal normalization enables case-specific normalization using the reference impact determined within the study [544]. On the other hand, external normalization is performed based on a selected reference system and is more appropriate when the relative importance of different indicators in a single system is determined. External normalization can dominate the weighting scheme and is not appropriate for comparative LCA study [545].

Since the objective of this study was to compare the impacts of DBPs control strategies, internal normalization was deemed suitable for impact interpretation. The internal normalization was performed using *Equation 7-2*.

$$N_{ij} = 1 - \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \qquad \textit{Equation 7-2}$$

where N is the normalized value of impact (e.g., climate change, ozone depletion), x is the value of impact category i under DBPs control strategy j. The max x_{ij} and min x_{ij} are the maximum (assigned value one) and minimum (assigned value zero) values in each impact category i.

<u>Stage 2-Interpretation:</u> Stage 2-Interpretation is performed by aggregation of midpoint impacts using the MCDM method that increases the usability, robustness and implementation of LCA [546]. Midpoint impact categories have been used extensively for LCA studies and are important for green building-related programs such as LEED, environmental product declarations etc. [546]. Numerous researchers have used midpoint impacts and combined them with other criteria such as human health risks, economic indicators etc., to rank the studied systems [544,547–550]. In the same vein, in order to represent possible preference variation of different stakeholders, 18 midpoint categories and the DBPs generated are aggregated under 3 main criteria: (1) Human health; (2)

Ecosystems; and (3) Resources. TOPSIS method is used to select the best DBPs control strategy with minimum impacts on the environment. TOPSIS is a widely used multi-criteria decision-making technique, in which the ideal solution is determined by identifying the most ideal and least ideal alternatives. The integration of LCA results into TOPSIS yields more robust solutions than those obtained from ReCiPe single scores and linear weighted sum methods [551,552].

The following six steps are used in TOPSIS to rank DBPs control strategies:

Step I: Normalizing the quantified impacts to human health, resources and eco-systems under different DBPs control strategies.

$$\overline{x}_{ij} = {x_{ij}}\Big/{\sqrt{\sum_{i=1}^{m} x^2{}_{ij}}} \qquad \textit{Equation 7-3}$$

DBPs concentrations in air and water are used as indicators of human health concern. The human health-related midpoint impacts and DBPs emissions are aggregated to the human health (HH) impact category, while other midpoint impacts are aggregated to the corresponding ecosystem (ES) and resources (RE) impact categories. The distribution of midpoint impacts into endpoints categories follows the same path as used for ReCiPe2016. All individual impacts are assumed to contribute equally into the main category.

Step II: Creating a weighted normalized matrix based on the weights determined for the three categories (HH, ES and RE) by stakeholders.

Step III: Evaluation of positive and negative ideal solutions. The best solutions (V_j^+) for the weighted normalized matrix are selected out of all alternatives:

$$V_j^+ = [Min_{HH}, Min_{ES}, Min_{RE}]$$

The worst solutions (V_j^-)for the weighted normalized matrix are also selected out of all alternatives

$$V_j^- = [Max_{HH}, Max_{ES}, Max_{RE}]$$

Step IV: Calculation of Euclidean distances between an alternative and positive (d_i^+)and negative (d_i^-) ideal solutions, respectively. Each DBPs control strategy is considered an alternative.

$$d_i^+ = \sqrt{\sum_{j=1}^{m}(v_{ij} - V_j^+)} \qquad \textit{Equation 7-4(a)}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}(v_{ij} - V_j^-)}$$ *Equation 7-4(b)*

Step V: The relative closeness to the ideal solution was found by Eq. (5-c)

$$CL_i^* = {d_i^-}\Big/{(d_i^- + d_i^+)}$$ *Equation 7-4(c)*

Step VI: Ranking DBPs control strategies based on the relative closeness calculated. The alternative with the smallest relative closeness is preferred.

The weights assigned to various criteria are subject to the stakeholders' preferences. In the absence of survey data on stakeholder preferences, the weights were changed from 0 to 1 to simulate stakeholders' preferences. Ternary plots are generated to visualize the change of ranking of DBPs control strategy changes with the variation in weights of the criteria.

7.2.5 Determine Eligible Incentives

Incentives for non-residential buildings such as aquatic centre can be determined as a percentage of energy saving per unit floor area. Higher the savings, more incentives will be applicable for the operation scenario. Based on the ranking results obtained from two interpretation stages, the energy savings are compared with each scenario. Based on the comparison, the impact of building operation environmental impacts on existing FIs eligibility criteria can be assessed.

7.3 Methodology Demonstration

The aquatic centre at the University of British Columbia (UBC), Vancouver, Canada, was selected as a case application of the P-LCA methodology. The aquatic centre is a new facility that has been granted a green building Leadership in Energy and Environmental Design (LEED) gold certification [553]. This facility consists of four types of swimming pools: a 50-m lap pool, a 25-m lap pool, a leisure pool with a variety of water recreational features (e.g., sprays, jets) and a hot tub (**Table 7-3)**.

The aquatic centre is equipped with an RWH system as a supplementary water source capable of supplying 2,700 m^3 of water annually [533]. The ISP hall with four pools (50-m, 25-m, leisure and hot tub pool) covers a total area of 3162.6 m^2 and are assumed to be in operation for 50 years' period. The UBC aquatic centre employs a combined HVAC system to remove DBPs from the air

The combined HVAC system consists of two AHUs and an LEV in the deck surrounding the pools. The pool water is also treated by combined chlorination and UV-treatment process. Though a number of DBPs control strategies are possible through a change in treatment and engineering systems this study focuses on strategies based on the change in the ventilation system. These strategies were adopted because they do not require additional resources and expenditure to implement, do not disturb pool operation and users.

Table 7-3 Characteristics of pools in UBC aquatic centre (*Source*:[554]) in the ISP

Description	50-m pool	25-m pool	Leisure pool	Hot tub
Design capacity (bathers)	200	353	374	34
Surface area (m^2)	1,251	534	347	31
Volume (m^3)	3,135.5	1,325.5	387.7	34.6
Average depth (m)	2.51	2.49	1.12	1.12
No. Of regenerative media filters	2	2	2	1
Flow rate (l/s)	177	95	120	40
Turnover duration (hour)	5	4	1	0.25
No. of pool refill per year	3	3	2	12

Note-UV: ultraviolet treatment; NaOCl: sodium hypochlorite

In total, seven DBPs control strategies (S1-S7) were investigated based on the operating conditions of AHUs and LEV (**Table 7-4**). These DBPs control strategies were developed and applied to the UBC aquatic centre in the study by Saleem et al. [555]. The DBPs concentrations reported in their study were used as part of LCI. The baseline case S1 represented the ISP operation without using any DBPs control strategy. The rest DBPs control strategies (S2-S7) were developed by changing the AHU fan speed and the amount of fresh air intake.

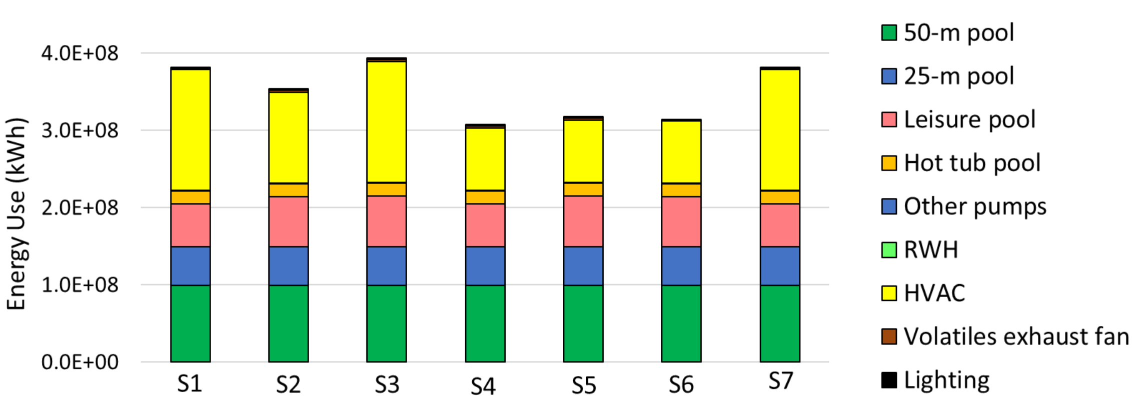
Table 7-4 DBPs control strategies used in UBC aquatic centre

Strategy	AHU 1		AHU 2		Local exhaust fan
	Fan Speed	Fresh Air	Fan Speed	Fresh Air	
S1	N	N (72%)	N	N (72%)	N
S2	N	86%	N	N (72%)	C
S3	N	100%	N	N (72%)	C
S4	-20%	N (72%)	-20%	N (72%)	C
S5	-10%	N (72%)	-10%	N (72%)	C
S6	N	N (72%)	N	C	C
S7	N	100%	N	C	C

Note-N: normal operating condition; C: closed (not operating)

7.3.1 Life Cycle Inventory

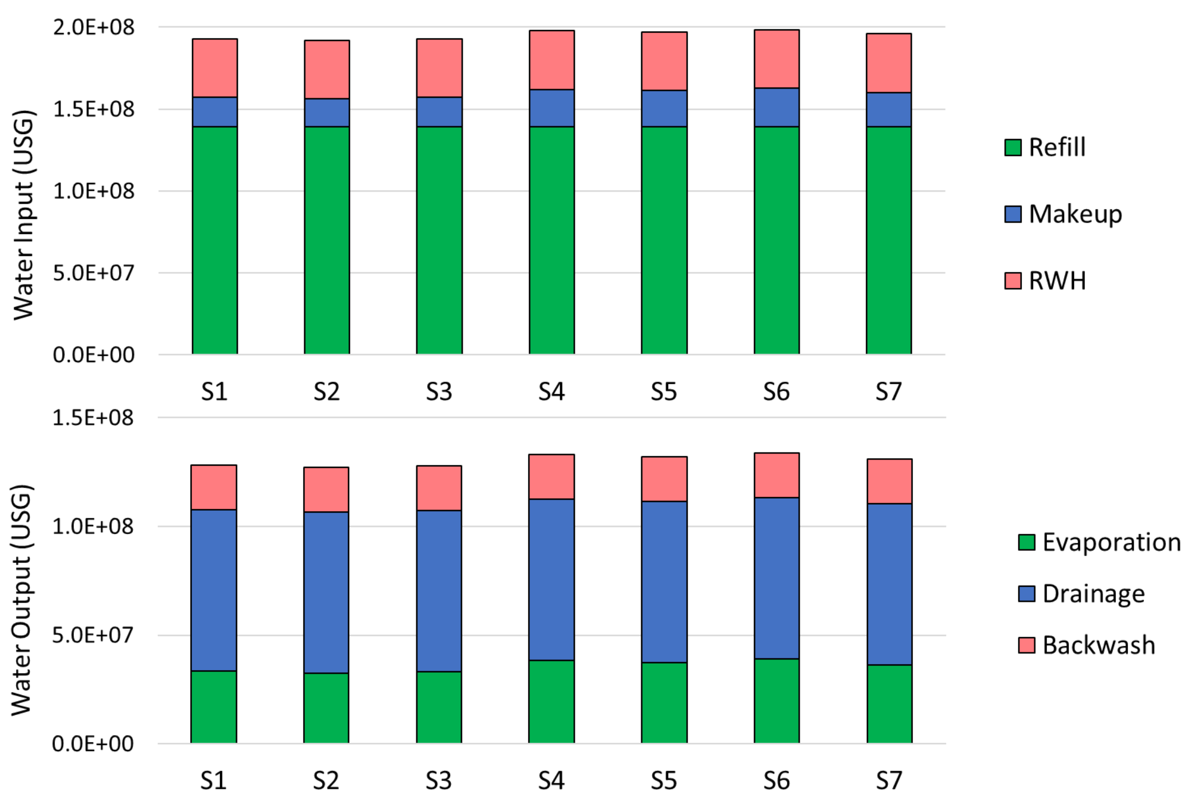
The detailed energy, chemical and water use related to seven DBPs control strategies are explained in the following sections. Energy use for operating the major ISP systems in the aquatic centre was estimated based on engineering drawings and schedules provided by the pool managers. The energy use included consumption by water treatment systems (UV-treatment and filtration), water and chemical pumps, RWH system, water heating system, water features in the leisure pool, lighting and HVAC system**. Figure 7-4** presents the breakdown of individual components' energy demands under seven DBPs control strategies. It was observed that the HVAC system's operation accounts for > 25% of the total energy consumption. The results are consistent with the results from previous studies, which also shown that the HVAC system consumes a major portion of the total energy used in aquatic centres [509,556]. For swimming pools, high energy consumption is due to the high water circulation rates required for maintaining the required water quality and operating water features. Among the four types of pools, the 50-m pool is the largest energy consumer (25-32%) due to the highest water use. A large amount of energy is required to circulate, disinfect and heat the water. The leisure pool consumes the third-highest amount of energy (15-21%) under different strategies. The high energy demand of this pool is due to the night pumps that ensure the pool water is continuously circulated to accommodate high bather loads. In addition, water features used in this pool also increased energy consumption, which accounts for 15% of this pool's total energy use. In comparison, the lighting system, LEV, additional pool pumps (bulk feed and super chlorinating) and the RWH system are associated with much lower energy consumption (≤ 1%) under all strategies.



Note-RWH: Rainwater harvesting; HVAC: Heating, ventilation and air conditioning system.

Figure 7-4 Energy use of ISP systems under DBPs control strategies

The water used to fill and operate the four pools was sourced from Metro Vancouver's drinking water system [557] and the RWH system [558]. The inventory generated for the ISP water use is provided in **Figure 7-5**. Since the strategies implemented mainly involved air circulation changes, the water use profile is almost constant. The variation of water loss under the seven strategies is correlated to the change of air circulation rate because the air circulation rate positively affects the rate of evaporation. Also, the 50-m pool has the largest surface, resulting in the highest water loss by evaporation. The highest water loss is due to drainage that varies within individual pools. RWH was able to compensate approximately 22% of the water loss to a certain degree, which helps achieve lower water usage. The water losses were determined the highest (1.34E+08 USG) for S6 and the lowest (1.27E+08 USG) for S2. The total water use within a 50-year period for all strategies was approximately 6.5×10^7 US gallons.



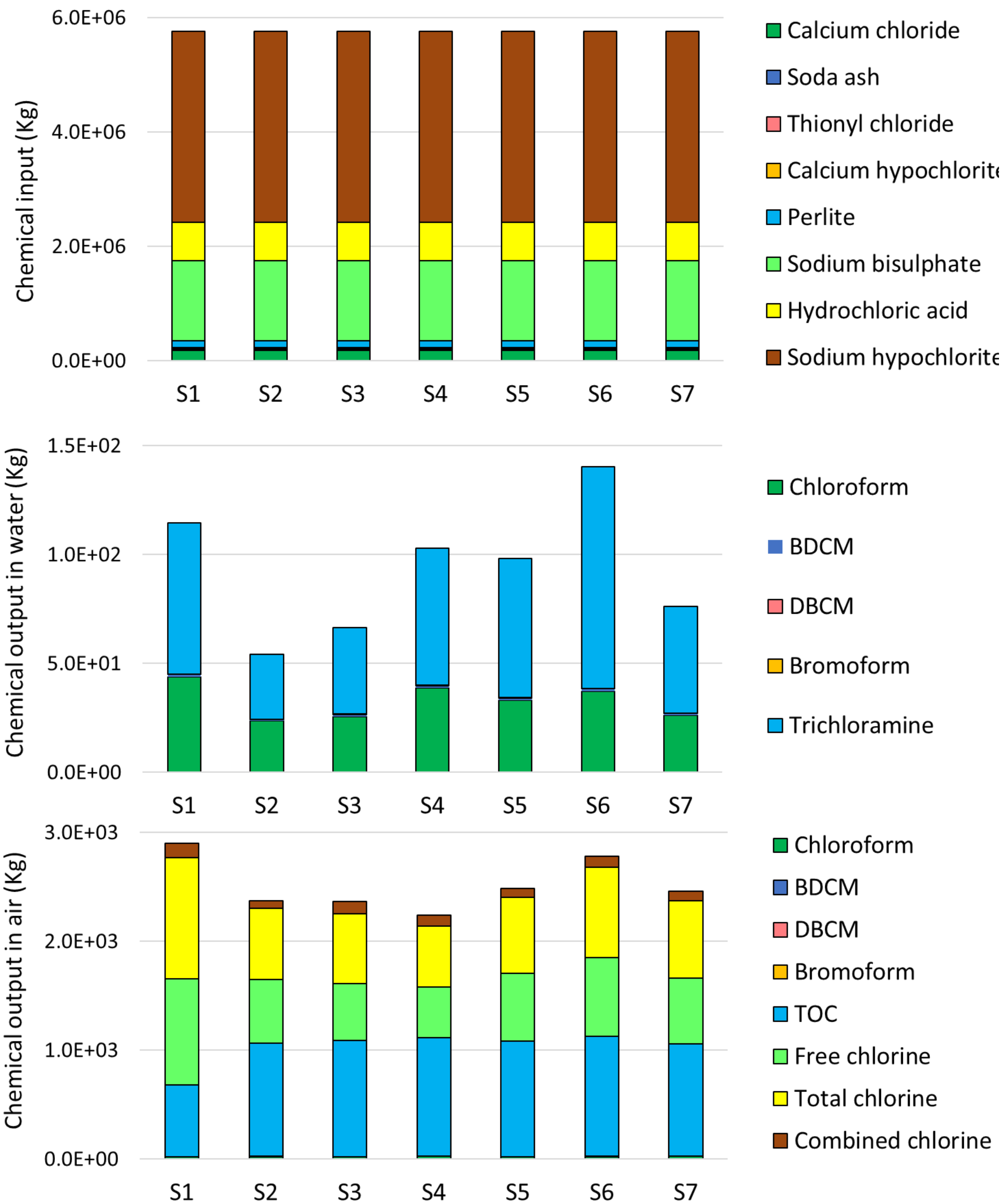
Note-RWH: Rainwater harvesting

Figure 7-5 Water use of ISP systems under DBPs control strategies

Figure 7-6 shows the chemical usage associated with seven DBPs control strategies. The aquatic centre employs combined chlorination and UV-filtration disinfection method [555]. The total concentration of THMs was used as a parameter indicating the chemical emissions to air and water due to limitation in data availability. The dosage data of disinfectants and other chemicals used for controlling water hardness and turbidity were provided by the facility manager [559], while the concentrations of THMs under different DBPs control strategies were obtained from field sampling and analysis [555]. Sodium hypochlorite, sodium bisulphate and hydrochloric acid were the most extensively used chemicals in the aquatic centre. A small quantity of calcium chloride was added to the pool water to maintain the acceptable level of calcium hardness.

Calcium hardness needs to maintain between 180-220 ppm in public swimming pools in British Columbia (Canada) [560]). The amount of chemical inputs was assumed to be constant for all DBPs control strategies during the service period. Saleem et al. [555] analyzed water samples for four THMs, total organic compounds (TOC), free chlorine, combined chlorine (an indicator of chloramines) and total chlorine; while air samples were analyzed for the four THMs and trichloramine. The measured emissions show distinct variations among DBPs control strategies. DBPs in water were found in a range of 26.3 to 95.5 μg/L and chloroform and trichloramine in air were ranged from 27.7 to 106.2 $\mu g/m^3$ and 0.052 to 0.224 mg/m^3, respectively, under the seven strategies [555].

Table 7-5 shows the life cycle impact assessment (LCIA) midpoint scores for the seven strategies or 18 midpoint environmental categories evaluated through ReCiPe Midpoint (H) V1.12. S3 and S7 showed higher environmental impacts in most categories except terrestrial ecotoxicity. Indoor DBPs released by both S3 and S7 were low compared to S4, S5 and S6; however, the two strategies were responsible for the higher energy consumption due to the need for heating a higher amount of fresh air. Hence, under these two strategies, better indoor air quality was reached at the expense of higher consumptions of resources. The higher environmental impacts point out the undesirability of S3 and S7. Terrestrial ecotoxicity impacts were determined to be highest for S1 and S6. Interestingly, for both strategies, chemical emissions were also high compared to other strategies.



Note-BDCM: bromodichloromethane; DBCM: dibromochloromethane; TOC: total organic compounds

Figure 7-6 Chemical use of ISP systems under DBPs control strategies

Table 7-5 ReCiPe Midpoint environmental impacts of DBPs control strategies applied on UBC aquatic centre

Environmental impact categories	Unit	S1	S2	S3	S4	S5	S6	S7
Climate change	kg CO_2-eq	4.1E+07	4.4E+07	4.9E+07	3.9E+07	4.0E+07	3.9E+07	4.7E+07
Ozone depletion	kg CFC-11 eq	6.4E+00	6.8E+00	7.5E+00	6.0E+00	6.2E+00	6.1E+00	7.3E+00
Human toxicity	kg 1,4-DB eq	2.5E+07	2.7E+07	3.0E+07	2.3E+07	2.4E+07	2.4E+07	2.9E+07
Agricultural land occupation	m^2	6.4E+07	6.9E+07	7.7E+07	6.0E+07	6.2E+07	6.2E+07	7.5E+07
Fossil depletion	kg oil eq	1.2E+07	1.3E+07	1.4E+07	1.1E+07	1.2E+07	1.2E+07	1.4E+07
Freshwater ecotoxicity	kg 1,4-DB eq	9.5E+05	1.0E+06	1.1E+06	9.0E+05	9.3E+05	9.2E+05	1.1E+06
Freshwater eutrophication	kg P eq	3.4E+04	3.6E+04	4.0E+04	3.2E+04	3.3E+04	3.2E+04	3.9E+04
Ionising radiation	kBq U235 eq	5.9E+06	6.4E+06	7.1E+06	5.6E+06	5.8E+06	5.7E+06	6.8E+06
Marine ecotoxicity	kg 1,4-DB eq	8.6E+05	9.2E+05	1.0E+06	8.1E+05	8.3E+05	8.3E+05	9.9E+05
Marine eutrophication	kg N eq	1.2E+04	1.3E+04	1.5E+04	1.2E+04	1.2E+04	1.2E+04	1.4E+04
Metal depletion	kg Fe eq	1.4E+06	1.5E+06	1.6E+06	1.4E+06	1.4E+06	1.4E+06	1.6E+06
Natural land transformation	m^2	7.0E+03	7.5E+03	8.3E+03	6.6E+03	6.8E+03	6.7E+03	8.0E+03
Particulate matter formation	kg PM_{10} eq	1.4E+05	1.5E+05	1.7E+05	1.3E+05	1.4E+05	1.4E+05	1.7E+05
Photochemical oxidant formation	kg NMVOC	1.3E+05	1.4E+05	1.5E+05	1.2E+05	1.2E+05	1.2E+05	1.5E+05
Terrestrial acidification	kg SO_2 eq	1.7E+05	1.8E+05	2.0E+05	1.6E+05	1.7E+05	1.6E+05	2.0E+05
Terrestrial ecotoxicity	kg 1,4-DB eq	8.4E+03	6.1E+03	7.2E+03	7.8E+03	7.9E+03	1.0E+04	7.7E+03
Urban land occupation	m^2a	5.0E+05	5.3E+05	5.9E+05	4.7E+05	4.8E+05	4.8E+05	5.7E+05
Water depletion	m^3	7.3E+06	7.8E+06	8.7E+06	6.8E+06	7.1E+06	7.0E+06	8.4E+06

Note-CFC-11: Chlorofluorocarbon; 1,4-DB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound

This indicates a proportional relationship between higher DBPs releases and terrestrial ecotoxicity. Although the energy associated with these two strategies is relatively low compared to S3 and S7, the higher amounts of DBPs released could increase the exposure for ISP users. S4 shows the lowest impacts in all impact categories except human toxicity, indicating its potential of achieving environmentally friendly ISP operation. Under S4, the fan speed of AHUs was reduced, which significantly lowered the energy use compared to other strategies. It is also seen that S4 is associated with high impacts in terrestrial ecotoxicity.

It is evident that S4 is associated with the overall lowest impacts, while S3 is associated with the highest impacts. The normalized results again indicate the feasibility of S4 for low impact ISP operation. Compared to the baseline case (S1), S2, S3 and S7 have very high environmental impacts, suggesting that providing a higher amount of fresh air (for example, compared to S1 fresh air quantity of 72%, S2, S3 and S7 are getting 86%, 100% and 100% air respectively) could reduce the levels of DBPs, but it could have a significant adverse impact on the environment. In the case study, building electricity was used as an energy source. The generation of electricity and other conventional energy are often associated with high environmental impacts [561].

A hotspot analysis was also performed to determine the most important processes and materials influencing the environmental impacts of ISP operation. The percentages of environmental impacts contributed by water, energy and chemical uses were compared for seven control strategies. The results show that the contribution of energy use was the highest (i.e., 87-94%) for all impact categories. The contributions of chemical and water use only account for ≤ 13% of the total impact under all strategies. In addition to the midpoint, ReCiPe 2016 Endpoint (H) V1.12 / World Recipe H method was used to determine the impacts of DBPs control strategies on human health, resources and ecosystem. These results are provided in Appendix G, Figure G1. The results show similar trends as a midpoint, i.e. S3 and S7 have the highest impacts while S4 has low impacts.

7.3.2 TOPSIS Results

The comparisons between environmental impacts and DBPs released can help ISP managers select the most suitable strategy with minimum environmental impacts. High DBPs levels emitted can cause direct human health impacts on ISP users. However, estimation of these direct human health impacts is beyond the scope of the proposed methodology. The TOPSIS was performed by considering three criteria under 21 sets of weights (Appendix G, Table G1). The best and worst cases for the ranking are shown in **Figure 7-7**.

The symbol at the convergence of the three criteria lines shows the most suitable DBPs control strategy for the specific weights in **Figure 7-7(a)**, while the symbol at the convergence of the three criteria in **Figure 7-7(b)** represent the least suitable strategy under the specific weight lines. The chemical use data included the amounts of chemicals used for all four pools annually; therefore, the LCA was not performed separately for the individual pools. It is observable from **Figure 7-7(a)** that S4 is the most suitable control strategy for the ISP understudy, which was ranked as the top alternative under 15 weighting scenarios. When the weight of human health increases, S2 and S5 become more suitable alternatives. This is due to the fact that the fresh air circulation rate is high in S2, which leads to a low concentration of DBPs in the ISP, while for S5, the reduced energy use leads to lower emissions related to energy production, resulting in a lower use of resources but a higher human health impact. The provision of fresh air is an important approach to improve indoor air quality [562]. Despite the low concentrations of DBPs, S3 is associated with very high environmental impacts, indicating that the improvement of air quality needs to be balanced with the overall environmental impact.

As shown in **Figure 7-7(b)**, S3 is the least suitable strategy under different weights; however, it is replaced by S6 when human health is given the maximum weight of 1 and ecosystems and resources are given a weight of zero, respectively. S6 is not favourable for human health protection considering the poor indoor air quality. This is because the LEV was switched off and the fresh air supply by the AHUs was reduced. Saleem et al. [555] also indicated that as the amount of fresh air entering the ISP decreases, the DBP levels in the air are likely to rise. The ranking of various DBPs control strategies suggests that the most promising alternative is S4 and the least favourable is S3.

Thus, the results of Stage 1 and 2 interpretation and endpoint impacts show that ranking of DBPs control strategies for environmental impacts show similar result that S4 is most suitable while S3 is least preferable. This study only focused on the interpretation of LCA results while direct human health impacts associated with indoor DBPs emissions were not determined. It is possible that DBPs control strategy with the lowest environmental impacts have high human health impacts.

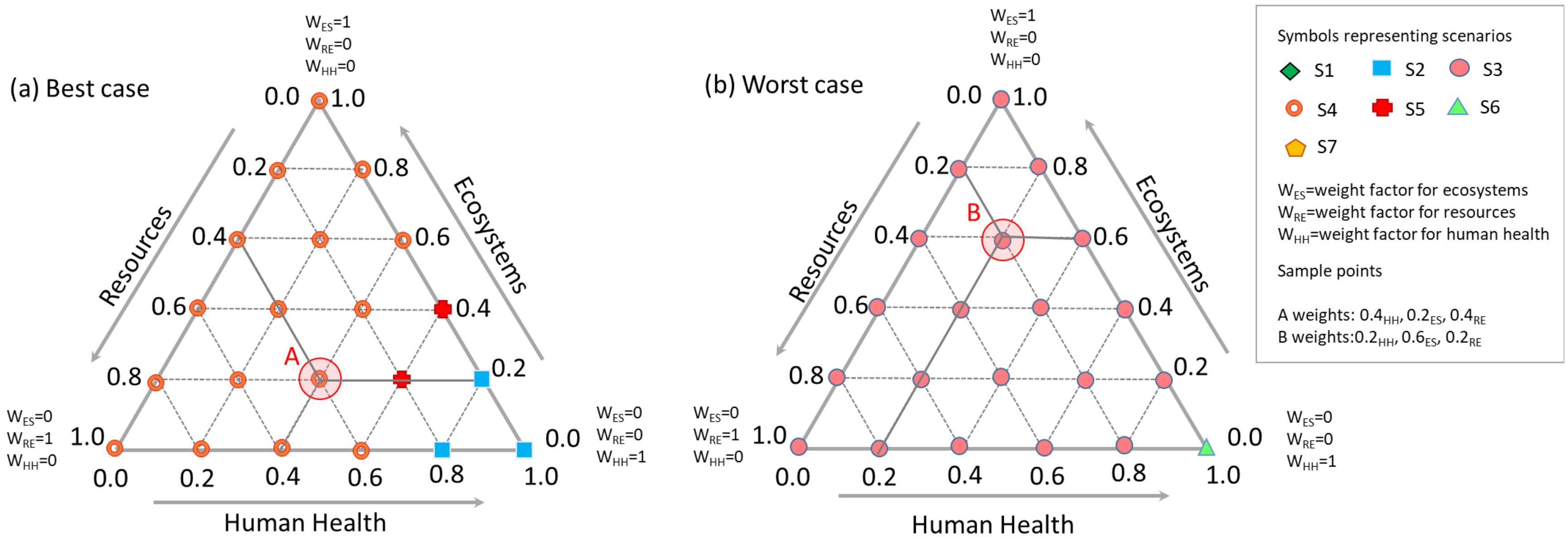


Figure 7-7 Ternary diagrams of ranking results of DPBs control strategies

In order to select DBPs control strategy that establishes a reasonable balance between LCA related environmental impacts and the direct human health risks, the current methodology can be integrated with human health risks evaluated for DBPs exposure to the users in a similar manner as proposed by Csiszar et al.[563].

7.3.3 Eligible Incentives

The incentives assigned to non-residential buildings are assigned according to the percentage of energy reduction. The inventory for the seven tested strategies showed that compared to base case S1, the energy savings increased by 7.5%, 18.2% and 15.9% for S2, S3 and S7 respectively, while they deceased 6.4% for S4 and 3.2% for S5. This implies that while the positive savings are eligible for incentives, extra operational bills will be needed for S4 and S5. However, S4 came to be the most suitable scenario for maximum environmental and health benefits. This implies that the most energy saving options are not necessarily the most optimal. Despite the importance of human health and environmental impacts that can result due to load shifting, FIs are predominantly emphasizing energy savings. Hence, there is need to revise existing FIs eligibility criteria and extend it to include degree of reduction in environmental impacts and human health risks.

7.4 Summary

The main objective of this chapter was to compare different DBPs control strategies or building operation strategies applied to the engineering systems and assess the environmental impacts using process-based LCA. The DBPs control strategies were developed by adjusting ISP operation conditions and thus the environmental impacts of DBPs control strategies are the same as those of different ISP operation methods. To meet this objective, a methodology is developed to facilitate ISP managers in selecting low impact DBPs control strategies for sustainable ISP management. The application of the methodology is illustrated using an indoor aquatic centre located in British Columbia (Canada). In particular, this study (i) generates an inventory of energy, water and chemicals used during the operation stage of an ISP; (ii) uses the inventory data to estimate the environmental impacts using the ReCipe method; (iii) enables prioritization of different DBPs control strategies using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [299]; and lastly (iv) revisit the eligibility criteria for FIs application. This study makes an original contribution by developing a methodology for estimating the environmental impacts of DBPs control strategies in ISPs. The outcomes of this study are expected to increase understanding of the link between DBPs control strategies and their potential environmental impacts, which will help select and implement suitable strategies for sustainable ISP management. The findings from this can also help improve existing ISP operation guidelines.

A case study of an ISP in Vancouver, Canada, was used to demonstrate the application of methodology. Seven strategies based on changes in ventilation rate and quantity of fresh air exchange were applied and compared. The results have shown that energy use in swimming pools was the major contributor to the environmental impacts (i.e., 87–94%), followed by chemical use and associated emissions. Since rainwater was used in the case study, the impacts from water use were relatively low. In most swimming pools, these impacts are expected to be higher than those estimated for the specific case study. These higher impacts are expected as the case study pool operates on hydroelectric energy while fossil fuels are still the most dominant source of electricity production around the world [564]. The results of P-LCA also showed that increase in ventilation rate and air quantity results in lower DBPs emissions, but the associated environmental impacts increased for the same strategies. Therefore, it is important for strategies to achieve a balance between the indoor DBPs levels and the environmental impacts generated by implementing DBPs control activities. The overall findings indicated that the proposed P-LCA methodology was suitable for the selection of a DBPs control strategy to operate a healthy and environmentally friendly ISP. Furthermore, the existing FIs criteria for GBs need to include the impacts on the environment and human health.

To conclude, there is a need to assess DBPs control strategies that ensure the healthy and sustainable operation of swimming pool facilities. Integration and assessment of DBPs control strategies with energy efficient technologies could be a path for future studies. The proposed P-LCA methodology can help in designing and implementing DBPs control strategies to achieve sustainable ISP operation and protection of human health from DBPs exposure.

Chapter 8 Conclusions and Recommendations

This research addresses critical gaps in the literature related to the evaluation of financial incentives' effectiveness and efficiency. A decision support framework was proposed and developed that can help attain low-energy green buildings and sustainable neighborhoods. The developed framework will help advance existing evaluation methods and direct financial resources to options that yield high environmental, health and cost-related benefits. The framework helps in decision making related to the selection of the most feasible operation strategy for public swimming pool facilities, selection of energy performance upgrades for new residential buildings based on occupancy profile of the residents, evaluation of cost and environmental effectiveness for residential archetypes and evaluation rebates efficiency of building and neighborhood levels. The framework will help end-users, developers, building managers and policy makers take informed decisions. Furthermore, though the framework is explicitly developed considering case studies in Canada, it can easily be replicated in other countries with similar social and economic conditions.

8.1 Summary

A summary of the specific study sections and the main conclusions are given below.

Chapter 3: An in-depth literature review was conducted on the types of financial incentives available for green buildings in Canada. Along with this, state-of-art practices employed for evaluation of the effectiveness of financial incentives were investigated. The findings of this chapter identify research gaps in financial incentives evaluation studies and different evaluation indicators and methodologies

Chapter 4: A systematic two-phase methodology was proposed to assess the impacts of occupancy on residential energy performance upgrade selection. Feasible EPUs were selected based on economic and environmental performance criteria and ranked through the TOPSIS method. The methodology was tested on two identical homes with different occupancy profiles. Calibrated energy models and detailed life cycle cost analysis were performed to observe the impact of occupancy. In addition, the methodology offered flexibility in describing the preference of occupants that could range from pro-economic to pro-environment. The proposed methodology in this chapter would assist developers, planners, potential owners and practitioners in developing single-family detached houses for retired as well as typical urban communities in Canada and other developed countries.

Chapter 5: This chapter provided a multi-stage methodology for evaluating the effectiveness of incentives available for new residential archetypes. The proposed methodology also introduced a location-based effectiveness index matrix that enables assessment of the environment and economic impacts of rebates from end-users' perspectives. In addition, a parametric sensitivity analysis approach is proposed that will enable the identification of the most important factors for obtaining effective rebates. The proposed methodology can help in understanding the relationship between FIs and their impact in achieving environmental and economic targets for different building archetypes. The case study conducted on seven residential archetypes common in Canada and showed the feasibility of the proposed methodology in making informed decisions. The results derived from the case study were used for providing recommendations for policy makers.

Chapter 6: The chapter proposed a methodology to evaluate the efficiency of FIs for residential archetypes at individual building and neighborhood level. The bottom-up energy modelling technique and data envelopment assessment method were used to obtain the feasibility of investment for different archetypes and climate zones. The methodology could determine efficiency from investors and government perspectives. This research can help municipality governments allocate rebates to archetypes, while the efficiency of investments can help end-users make informed decisions regarding their future expenditure. At neighborhood levels, the efficiency could help in the distribution of national and provincial subsidies. Likewise, the investment efficiency at neighborhood level can help to benchmark and comparing regions and indicate what changes need to be incorporated for improvement in performance.

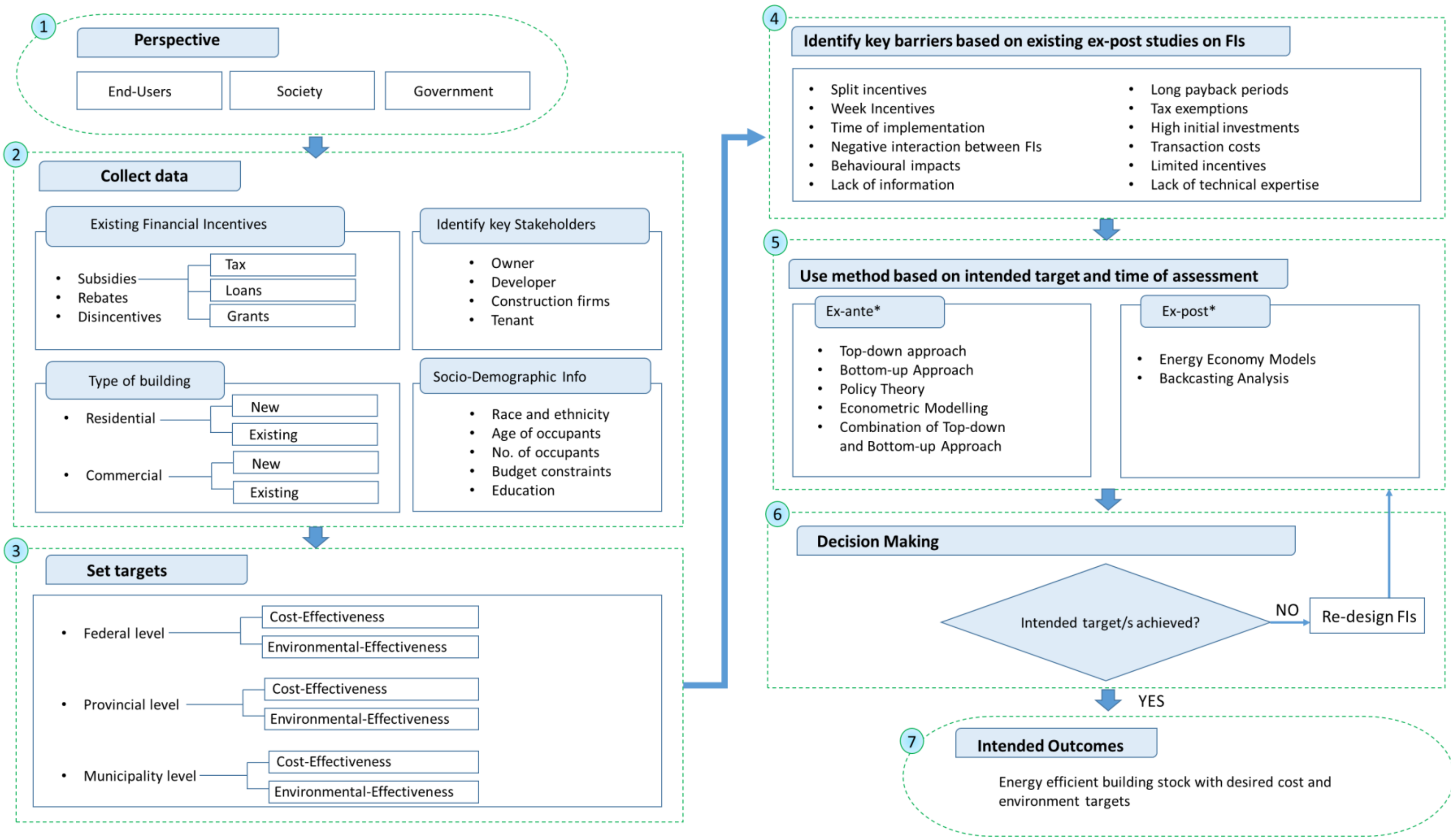
Chapter 7: A methodology for evaluating the most feasible operation strategies for public indoor swimming pools based on health and environmental perspective. The methodology was developed on detailed energy modelling, field study data and process-based life cycle assessment to obtain environmental and health impacts. In addition, the relation between eligible incentives and building operation was observed. The research in this chapter fulfilled the significant knowledge gap in the literature related to environmental impact evaluation of public indoor swimming pool facilities. A case study of an actual facility in Vancouver, Canada, was considered. The results indicated the feasibility of methodology to assess the environment and human health impacts along with implication related to eligible public incentives. The proposed methodology can help in designing and implementing strategies that can help achieve sustainable ISP operation and protection of human health from swimming pool disinfectant by-products exposure.

8.2 Conclusions

The aim of the study was to develop a planning framework for financial incentives to enhance the construction of green buildings (GBs). The framework was demonstrated by case studies of actual buildings and a hypothetical community. It was clear from the findings that the local, regional parameters (location, building archetype, community design, costs, energy prices), occupancy (number of occupants), building operation and stakeholders' perspectives play an important role in the effectiveness and efficiency of available financial incentives. The findings can be useful for policy makers, end-users, developers and building managers to achieve more energy savings and carbon emissions reductions at a lower life cycle cost.

Based on research findings, a seven-step methodology is proposed to obtain the desired effectiveness of FIs in residential and commercial buildings (**Figure 8-1**). These steps include: (1) Consideration of major stakeholders' perspectives in order to minimize the associated risks; (2) Collection of data related to the buildings that include existing incentives, occupancy profiles, socio-demographic conditions and stakeholders; (3) Regulatory level to assess the degree of influence of deployed FIs as well as the available resources; (4) Identification of key barriers that may influence effectiveness is essential to assure minimum wastage of resources; (5) Applicable analysis method (ex-post or ex-ante) depending upon the time of analysis, for example, the ex-ante method is the only option for analysis for new FIs (for instance, a new technology); (6) Comparison of the analysis results with the desired target; and (7) revision if targets are not achieved.

In addition, a strategic map (**Figure 8-2)** is generated that can be used to develop more energy efficient building stocks and more sustainable cities. The map shows that depending upon the level of application, the main targets, key policy instruments and influence of associated stakeholders will change. The design and deployment of future FIs need to be gradual and planned to ensure that municipality, regional, provincial and national targets are achieved.



*These are all the most commonly used ex-post and ex-ante methods. Only one method will be selected according to perspective and target under consideration

Figure 8-1 Methodology for evaluating the effectiveness of FIs

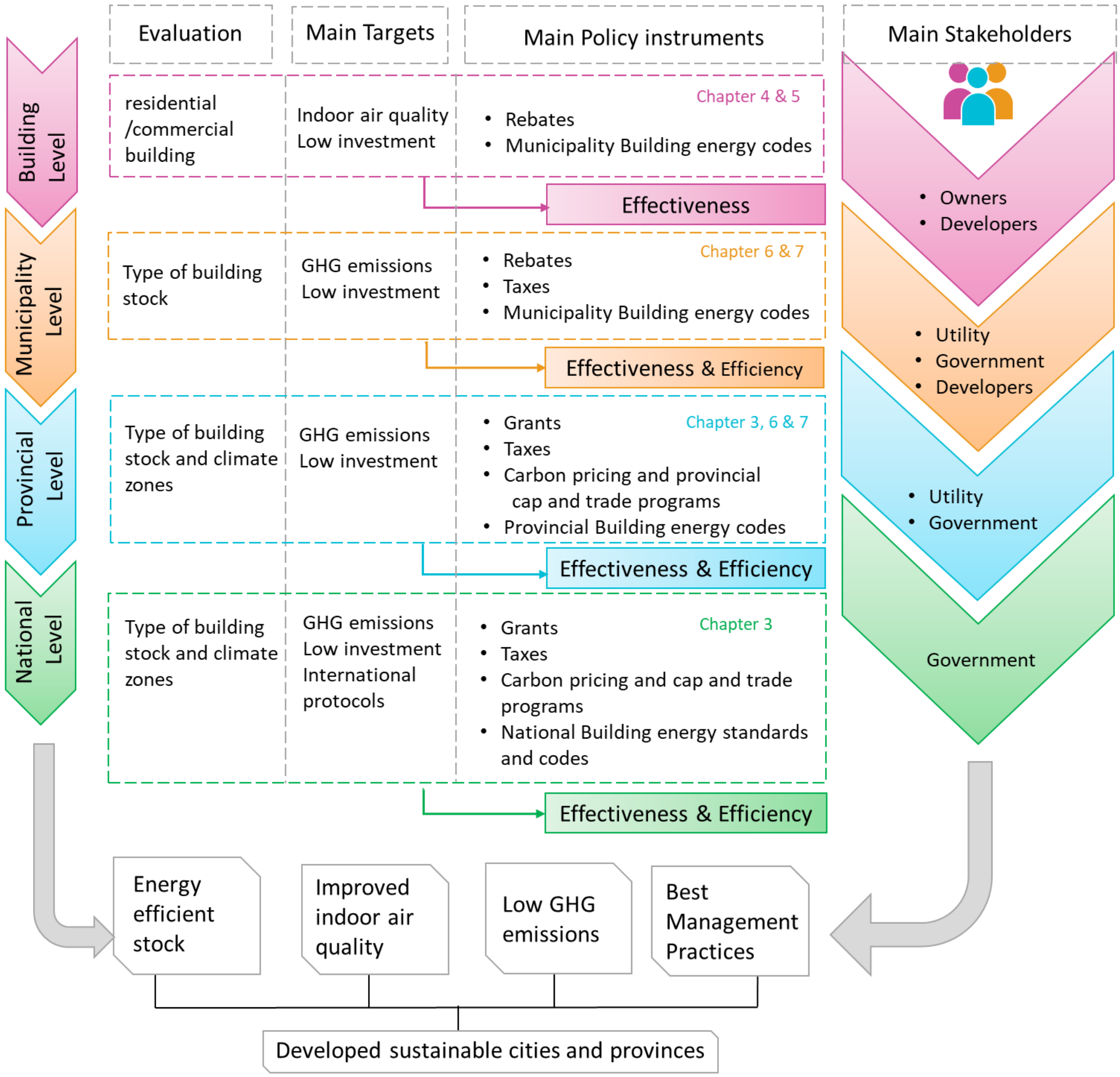


Figure 8-2 Strategic Map

8.3 Originality and Contributions

The study critically evaluated green building financial incentives in Canada. The work will help design and modify FIs for the wider adaptation of GBs to meet climate goals in Canada. In summary, three major contributions of this research are as follows.

Standardization of FIs appraisal: There is no standard method of FIs effectiveness and efficiency evaluation and different methods have been employed to achieve their results. Hence, this framework strived to provide a standard decision support framework for evaluating green building FIs based on effectiveness and efficiency that will enable engineers, planners and policy makers to make informed decisions.

Multi-stakeholders' perspectives in investment planning: In order to ensure a sustainable future, all stakeholders of buildings should strive towards the same goal. The two most important stakeholders are the investors (end-users, occupants or developers) and the government providing rebates. Most studies have considered only one perspective evaluation. Hence, the research results provide useful information to help in decision making by investors and the government.

Incorporation of lifecycle thinking and spatial variations: Limited studies have evaluated the effectiveness and efficiency of the deployed financial incentives. Moreover, the FIs associated with the achievement of specific building energy code targets are absent from the literature. This research proposed effectiveness and efficiency evaluation frameworks that can account for the change in residential building archetype and climate zone for meeting advanced building energy code targets.

8.4 Limitations

Data limitations: *D*ata collection related to buildings costs and energy usage is a challenge. This research utilized data from a number of sources, including the RSMeans database, local utility providers, ASHRAE, field measurements and existing literature. Hence, there is non-uniformity in data and assumptions are often made to generate the models with limited data available. Since the purpose of this research was to provide a framework that is capable of evaluating the effectiveness and efficiency of FIs, data limitation did not have a significant impact on decision making and reasonable results were obtained.

Focus on one form of financial incentive: The framework proposed utilized only one form of incentive, i.e., rebates offered by the government. Although rebates are the most common policy instruments and highest among existing FIs, other incentives such as grants and taxes can also help in increasing the rate of construction of greener buildings. Therefore, future work can incorporate impact of these instruments combined to determine overall impacts of energy policies at local and national levels.

Limited to developed countries: The framework was constructed under the Canadian context and case studies of Canadian buildings were employed. Hence the obtained results can be applied to other countries with a similar economic and social condition like the United States and the United Kingdom. However, the framework cannot be applied to developing countries unless suitable modifications are made according to governing parameters of developing countries.

Limited to new buildings: The framework was introduced for new buildings; however, it can be modified and applied to retrofit existing buildings through careful evaluation and classification of existing archetypes. Compared to new houses, existing homes are more complex and will have a larger set of constraints that will vary with the local context. Detailed survey studies will be required to identify the archetypes of the existing building stock and designing effective and efficient FIs.

Limited number of EPUs: Despite an extensive study on a number of archetypes of residential buildings, there are some limitations that need to considered for applying the framework results. A limited number of locally available EPUs were utilized for rebates effectiveness evaluation. Future studies should carefully consider the local context and construction practices during FIs assessment.

Limited Statistical Analysis: A limited statistical analysis was conducted to investigate the effect of different design and economic parameters on ultimate effectiveness and efficiency of tested incentives. A detailed multivariate sensitivity analysis is required to determine the impact of uncertain parameters on performance of FIs and to propose improvements in current incentive structures.

8.5 Future Research

The following areas were identified as a possible extension of this research.

Incorporate economic uncertainty: Future research should consider economic uncertainties related to interest rates, energy prices, labor and digression costs [47,391,392]. Costs of low-emission and renewable systems are expected to decrease as more efficient equipment and technologies are developed and GBs become more widely adopted. Hence, the investors will have wider choices of EPUs for making energy efficient buildings.

Incorporate the impact of climate change: Climate change is another important factor that will affect the selection of EPUs and the effectiveness and efficiency of FIs in the near future. A recent report by Canada's Changing Climate Report indicates Canada's temperature is rising at rates twice compared to the other regions of the world [565]. Hence, the cooling load demands of buildings will increase over time. Therefore, future studies should consider the impact of climate change on the EPUs selection for residential buildings.

Incorporate the impact of the COVID-19 pandemic and changing occupancy profiles: Another area of research that needs to be addressed urgently is the impact of the COVID-19 pandemic on occupants' behavior and the relevant EPUs for increased occupancy periods. Energy use in residential buildings has increased as people spend the majority of their time at home as an intervention measure [338]. As a result of this pandemic, homes have been transformed into mixed-use spaces where home-schooling, office work, recreational activities and social interaction have become norms. Similarly, the percentage of remote or home workers had been steadily increasing in Canada and other countries of the world, even in pre-pandemic conditions. COVID-19 has increased the trend of working from homes, thus bringing permanent changes in the energy use of the building sector [339,340]. These changing dynamics of building energy usage should be an essential part of FIs designs and need to be considered when implementing FIs policies.

References

[1] Cabeza LF, Ürge-Vorsatz D. The role of buildings in the energy transition in the context of the climate change challenge. Global Transitions 2020; 2:257–60. doi:https://doi.org/10.1016/j.glt.2020.11.004.

[2] Yudelson J. The green building revolution. Island Press; 2008.

[3] United States Environmental Protection Agency (EPA). Green building basic information. 2011.

[4] Finch ME. Green Realities: The Financial Opportunities of Environmentally Sensitive by. Massachusetts Institute of Technology., 1999.

[5] US EPA. Basic Information: Green Buildings. United States Environmental Protection Agency (US EPA) 2012. https://archive.epa.gov/greenbuilding/web/html/ (accessed July 11, 2017).

[6] Zhang X, Wu Z, Feng Y, Xu P. "Turning green into gold": a framework for energy performance contracting (EPC) in China's real estate industry. Journal of Cleaner Production 2015; 109:166–73. doi:10.1016/j.jclepro.2014.09.037.

[7] Carbon Trust. The UK Climate Change Programme: Potential evolution for business and the public sector. 2005.

[8] Gluch P, Gustafsson M, Thuvander L, Baumann H. Charting corporate greening: Environmental management trends in Sweden. Building Research and Information 2014; 42:318–29. doi:10.1080/09613218.2014.855873.

[9] Häkkinen T, Belloni K. Barriers and drivers for sustainable building. Building Research & Information 2011; 39:239–55. doi:10.1080/09613218.2011.561948.

[10] Sayce S, Ellison L, Parnell P. Understanding investment drivers for UK sustainable property. Building Research and Information 2007; 35:629–43. doi:10.1080/09613210701559515.

[11] United Nations Environment Programme (UNEP), (SBCI) SB and CI. Buildings and Climate Change: Summary for decision-makers 2009.

[12] Kosheleva E, Elliott J. Green building in the russian context: An investigation into the establishment of a leed®-based green building rating system in the Russian federation. Journal of Green Building 2006; 1:105–23. doi:10.3992/jgb.1.3.105.

[13] Bartlett E, Howard N. Building Research & Information Informing the decision makers on the cost and value of green building Informing the decision makers on the cost and value of green building 2000; 5–6. doi:10.1080/096132100418474.

[14] Bordass B. Cost and value: Fact and fiction. Building Research and Information 2000; 28:338–52. doi:10.1080/096132100418492.

[15] Yildirim ŞU. he Applicability of Current Green Building Incentive Models to the Turkish Property Market,. Mimar Sinan Fine Arts University, Istanbul., 2014.

[16] Huo X, Yu ATW. Analytical review of green building development studies. Journal of Green Building 2017; 12:130–48. doi:10.3992/1943-4618.12.2.130.

[17] Shazmin SAA, Sipan I, Sapri M. Property tax assessment incentives for green building: A review. Renewable and Sustainable Energy Reviews 2016; 60:536–48. doi:10.1016/j.rser.2016.01.081.

[18] Olubunmi OA, Xia PB, Skitmore M. Green building incentives: A review. Renewable and Sustainable Energy Reviews 2016; 59:1611–21. doi:10.1016/j.rser.2016.01.028.

[19] Qian QK, Fan K, Chan EHW. Regulatory incentives for green buildings: gross floor area concessions. Building Research & Information 2016; 44:675–93. doi:10.1080/09613218.2016.1181874.

[20] Steg L, Dreijerink L, Abrahamse W. Why are energy policies acceptable and effective? Environment and Behavior 2006;38:92–111. doi:10.1177/0013916505278519.

[21] Rana A, Sadiq R, Alam MS, Karunathilake H, Hewage K. Evaluation of financial incentives for green buildings in Canadian landscape. Renewable and Sustainable Energy Reviews 2021; 135. doi:10.1016/j.rser.2020.110199.

[22] Horan K. Evaluating the Energy Returns of Investment-Based Incentive Programs: The Case of Oregon's Business Energy Tax Credits. University of Oregon, 2011.

[23] Abolhosseini S, Heshmati A. The main support mechanisms to finance renewable energy development. Renewable and Sustainable Energy Reviews 2014; 40:876–85. doi:10.1016/j.rser.2014.08.013.

[24] Ramírez FJ, Honrubia-Escribano A, Gómez-Lázaro E, Pham DT. Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for European countries. Energy Policy 2017; 102:440–52. doi:10.1016/j.enpol.2016.12.040.

[25] UNEP-SBCI. Buildings and Climate Change: Summary for Decision Makers. Buildings and Climate Change: Summary for Decision-Makers 2009:1–62. doi:10.1127/0941-2948/2006/0130.

[26] Gündes S, Yildirim SU. The use of incentives in fostering green buildings. Metu Journal of the Faculty of Architecture 2015; 32:45–59. doi:10.4305/METU.JFA.2015.2.3.

[27] Gabrielli L, Ruggeri AG. Developing a model for energy retrofit in large building portfolios: Energy assessment, optimization and uncertainty. Energy and Buildings 2019; 202. doi:10.1016/j.enbuild.2019.109356.

[28] Prada A, Cappelletti F, Gasparella A. Optimization of government subsidization strategies for building stock energy refurbishment. 7th International Building Physics Conference IBPC2018, Syracuse, NY: 2018, p. 1277–88. doi:14305/ibpc.2018.pe-1.04.

[29] Liao Z. The evolution of wind energy policies in China (1995-2014): An analysis based on policy instruments. Renewable and Sustainable Energy Reviews 2016; 56:464–72. doi:10.1016/j.rser.2015.11.097.

[30] He K, Lei Y, Pan X, Zhang Y, Zhang Q, Chen D. Co-benefits from energy policies in China. Energy 2010; 35:4265–72. doi:10.1016/j.energy.2008.07.021.

[31] Li L, Tan Z, Wang J, Xu J, Cai C, Hou Y. Energy conservation and emission reduction policies for the electric power industry in China. Energy Policy 2011; 39:3669–79. doi:10.1016/j.enpol.2011.03.073.

[32] Giacone E, Mancò S. Energy efficiency measurement in industrial processes. Energy 2012; 38:331–45. doi:10.1016/j.energy.2011.11.054.

[33] Asadi E, da Silva MG, Antunes CH, Dias L. A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. Building and Environment 2012; 56:370–8. doi:10.1016/j.buildenv.2012.04.005.

[34] La Rosa AD, Recca A, Gagliano A, Summerscales J, Latteri A, Cozzo G, et al. Environmental impacts and thermal insulation performance of innovative composite solutions for building applications. Construction and Building Materials 2014; 55:406–14. doi:10.1016/j.conbuildmat.2014.01.054.

[35] Ingrao C, Scrucca F, Tricase C, Asdrubali F. A comparative Life Cycle Assessment of external wall-compositions for cleaner construction solutions in buildings. Journal of Cleaner Production 2016; 124:283–98. doi:10.1016/j.jclepro.2016.02.112.

[36] Pombo O, Rivela B, Neila J. Life cycle thinking toward sustainable development policy-making: The case of energy retrofits. Journal of Cleaner Production 2019; 206:267–81. doi:10.1016/j.jclepro.2018.09.173.

[37] ANTONIADES H. The Application of Taxation Benefits and Incentives for Green Buildings. State of Australian Cities (SOAC) Conference, 2011.

[38] Penna P, Prada A, Cappelletti F, Gasparella A. Multi-objectives optimization of Energy Efficiency Measures in existing buildings. Energy and Buildings 2015; 95:57–69. doi:10.1016/j.enbuild.2014.11.003.

[39] Jafari A. Decision-making framework for the selection of sustainable alternatives for energy-retrofits. University of New Mexico, 2018.

[40] Ouf M, O'brien W. Occupant modeling for code compliance and incentive programs ASHRAE Multidisciplinary Task Group on Occupant Behavior in Buildings View project IEA EBC Annex 79: Occupant-centric building design and operation View project. 2018.

[41] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews 2014; 29:394–416. doi:10.1016/j.rser.2013.08.037.

[42] Jönsson Å. Is it feasible to address indoor climate issues in LCA? Environmental Impact Assessment Review 2000; 20:241–59. doi:10.1016/S0195-9255(99)00039-6.

[43] Hellweg S, Demou E, Scheringer M, Mckone TE, Hungerbuhler K. Confronting workplace exposure to chemicals with LCA: Examples of trichloroethylene and perchlorpethylene in metal degreasing and dry cleaning. Environmental Science and Technology 2005;39:7741–8. doi:10.1021/es047944z.

[44] Buonocore JJ, Levy JI, Guinto RR, Bernstein AS. Climate, air quality, and health benefits of a carbon fee-and-rebate bill in Massachusetts, USA. Environmental Research Letters 2018;13. doi:10.1088/1748-9326/aae62c.

[45] Rossner A, Jordan CE, Wake C, Soto-Garcia L. Monitoring of carbon monoxide in residences with bulk wood pellet storage in the Northeast United States. Journal of the Air and Waste Management Association 2017; 67:1066–79. doi:10.1080/10962247.2017.1321054.

[46] Survilo MF. Indoor Air Quality Impacts of a Woodstove Exchange Program in Washington County, Oregon. Portland State University, 2020.

[47] Rysanek AM, Choudhary R. Optimum building energy retrofits under technical and economic uncertainty. Energy and Buildings 2013; 57:324–37. doi:10.1016/j.enbuild.2012.10.027.

[48] McKinsey & Company. Unlocking energy efficiency in the U.S. economy. 2009.

[49] Liu X, Liu X, Luo X, Fu H, Wang M, Li L. Impact of Different Policy Instruments on Diffusing Energy Consumption Monitoring Technology in Public Buildings: evidence from Xi' an, China. Journal of Cleaner Production 2020; 251. doi:10.1016/j.jclepro.2019.119693.

[50] Blum H, Atkinson B, Lekov AB. A methodological framework for comparative assessments of equipment energy efficiency policy measures. Energy Efficiency 2013;6:65–90. doi:10.1007/s12053-012-9162-x.

[51] Lim TH, De Kleine RD, Keoleian GA. Energy use and carbon reduction potentials from residential ground source heat pumps considering spatial and economic barriers. Energy and Buildings 2016; 128:287–304. doi:10.1016/j.enbuild.2016.06.060.

[52] Hong T, Lee M, Kang H. Framework for Optimizing the Solar Incentive from the Perspectives of Residents and Policy Makers. Renewable Energy Integration with Mini/Microgrid – Proceedings of REM2016, vol. 103, Maldives: 2016, p. 189–94. doi:10.1016/j.egypro.2016.11.271.

[53] Ma B, Song G, Smardon RC, Chen J. Diffusion of solar water heaters in regional China: Economic feasibility and policy effectiveness evaluation. Energy Policy 2014; 72:23–34. doi:10.1016/j.enpol.2014.04.015.

[54] Zhang J, Cho H, Knizley A. Evaluation of financial incentives for combined heat and power (CHP) systems in U.S. regions. Renewable and Sustainable Energy Reviews 2016; 59:738–62. doi:10.1016/j.rser.2016.01.012.

[55] Hossaini Fard N. Towards net zero buildings assessment framework: a natural capital approach. University of British Columbia, n.d.

[56] Sun K, Hong T. A framework for quantifying the impact of occupant behavior on energy savings of energy conservation measures. Energy and Buildings 2017;146:383–96. doi:10.1016/j.enbuild.2017.04.065.

[57] Calì D, Osterhage T, Streblow R, Müller D. Energy performance gap in refurbished German dwellings: Lesson learned from a field test. Energy and Buildings 2016;127:1146–58. doi:10.1016/j.enbuild.2016.05.020.

[58] Yan D, Hong T, Dong B, Mahdavi A, D'Oca S, Gaetani I, et al. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. Energy and Buildings 2017; 156:258–70. doi:10.1016/j.enbuild.2017.09.084.

[59] Bahaj A, James P. Urban energy generation: The added value of photovoltaics in social housing. Renewable and Sustainable Energy Reviews 2007; 11:2121–36. doi:10.1016/j.rser.2006.03.007.

[60] Saldanha N, Beausoleil-Morrison I. Measured end-use electric load profiles for 12 Canadian houses at high temporal resolution. Energy and Buildings 2012; 49:519–30. doi:10.1016/j.enbuild.2012.02.050.

[61] Lomas KJ. Editorial: Carbon reduction in existing buildings: A transdisciplinary approach. Building Research and Information 2010; 38:1–11. doi:10.1080/09613210903350937.

[62] Delzendeh E, Wu S, Lee A, Zhou Y. The impact of occupants' behaviours on building energy analysis: A research review. Renewable and Sustainable Energy Reviews 2017; 80:1061–71. doi:10.1016/j.rser.2017.05.264.

[63] Li S, Hu D, Cai J, Cai H. Real option-based optimization for financial incentive allocation in infrastructure projects under public-private partnerships. Frontiers of Engineering Management 2020; 7:413–25. doi:10.1007/s42524-019-0045-0.

[64] Salat S. Energy loads, CO2 emissions and building stocks: Morphologies, typologies, energy systems and behaviour. Building Research and Information 2009; 37:598–609. doi:10.1080/09613210903162126.

[65] Silva M, Oliveira V, Leal V. Urban Form and Energy Demand: A Review of Energy-relevant Urban Attributes. Journal of Planning Literature 2017; 32:346–65. doi:10.1177/0885412217706900.

[66] Ewing R, Rong F. The impact of urban form on U.S. residential energy use. Housing Policy Debate 2008; 19:1–30. doi:10.1080/10511482.2008.9521624.

[67] Government of Canada. Greenhouse gas emissions - Canada. 2019.

[68] NRCan. Energy efficiency trends in Canada 2019. https://oee.nrcan.gc.ca/publications/statistics/trends/2015/totalsectors.cfm (accessed June 3, 2020).

[69] The Government of British Columbia. BC Energy Step Code 2018.

[70] Rana A, Hewage K, Alam MS, Sadiq R. Financial incentives for green residential buildings in Canada: A review from a regulatory lens. 6th CSCE-CRC International

Construction Specialty Conference 2017 - Held as Part of the Canadian Society for Civil Engineering Annual Conference and General Meeting 2017, vol. 1, 2017.

[71] Hepburn C, O'Callaghan B, Stern N, Stiglitz J, Zenghelis D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? Oxford Review of Economic Policy 2020; 36.

[72] IEA. Energy Efficiency: Buildings-The global exchange for energy efficiency policies, data and analysis. IEA 2019.

[73] Cotten MN. The Wisdom of LEED' s Role in Green Building Mandates The Wisdom of LEED' s Role in Green Building Mandates. Cornell Real Estate Review 2012; 10:22–37.

[74] Taylor JM. Sustainable Building Practices: Legislative and Economic Incentives. Management and Innovation for a Sustainable Built Environment MISBE 2011, Amsterdam: 2011.

[75] Datta S, Gulati S. Utility rebates for ENERGY STAR appliances: Are they effective? Journal of Environmental Economics and Management 2014; 68:480–506. doi:10.1016/j.jeem.2014.09.003.

[76] Du Can S de la R, Leventis G, Phadke A, Gopal A. Design of incentive programs for accelerating penetration of energy-efficient appliances. Energy Policy 2014:56–66. doi:10.1016/j.enpol.2014.04.035.

[77] Ríos JR, Olaya Y. A dynamic analysis of strategies for increasing energy efficiency of refrigerators in Colombia. Energy Efficiency 2018; 11:733–54. doi:10.1007/s12053-017-9601-9.

[78] Harmelink M, Nilsson L, Harmsen R, Harmelink M, Harmsen R, Nilsson L. Theory-based policy evaluation of 20 energy efficiency instruments. Energy Efficiency 2008; 1:131–48. doi:10.1007/s12053-008-9007-9.

[79] Climate Action Tracker. A government roadmap for addressing the climate and post COVID-19 economic crises 2020.

[80] Sebi C, Nadel S, Schlomann B, Steinbach J. Policy strategies for achieving large long-term savings from retrofitting existing buildings. Energy Efficiency 2019; 12:89–105. doi:10.1007/s12053-018-9661-5.

[81] Bertoldi P, Economidou M, Palermo V, Boza-Kiss B, Todeschi V. How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. WIREs Energy and Environment 2020. doi:10.1002/wene.384.

[82] Liu G, Tan Y, Li X. China's policies of building green retrofit: A state-of-the-art overview. Building and Environment 2020; 169. doi:10.1016/j.buildenv.2019.106554.

[83] Curtin J, McInerney C, Ó Gallachóir B. Financial incentives to mobilise local citizens as investors in low-carbon technologies: A systematic literature review. Renewable and Sustainable Energy Reviews 2017; 75:534–47. doi:10.1016/j.rser.2016.11.020.

[84] Hoicka CE, Parker P, Andrey J. Residential energy efficiency retrofits: How program design affects participation and outcomes. Energy Policy 2014; 65:594–607. doi:10.1016/J.ENPOL.2013.10.053.

[85] Nadel SM, Atkinson BA, McMahon JE. A review of US and Canadian lighting programs for the residential, commercial, and industrial sectors. Energy 1993; 18:145–58. doi:10.1016/0360-5442(93)90098-X.

[86] Stern PC, Aronson E, Darley JM, Hill DH, Hirst E, Kempton W, et al. The Effectiveness of Incentives for Residential Energy Conservation. Evaluation Review 1986; 10:147–76. doi:10.1177/0193841X8601000201.

[87] Bowen GA. Document Analysis as a Qualitative Research Method. Qualitative Research Journal 2009; 9:27–40. doi:10.3316/QRJ0902027.

[88] Mansilla VB, Duraising ED. Targeted Assessment of Students' Interdisciplinary Work: An Empirically Grounded Framework Proposed. The Journal of Higher Education 2007; 78:215–37. doi:10.1080/00221546.2007.11780874.

[89] Togia A, Tsigilis N. Impact factor and education journals: a critical examination and analysis. International Journal of Educational Research 2006; 45:362–79. doi:10.1016/j.ijer.2007.02.001.

[90] Government of Canada. Greenhouse gas emissions - Canada.ca 2019. https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html (accessed January 27, 2020).

[91] NRCan. Energy Use Data Handbook, 1990–2014. Ottawa (ON): 2014.

[92] Government of Canada. Government of Canada sets ambitious GHG reduction targets for federal operations 2017.

[93] OEE. Office of Energy Efficiency. NRCan 2018.

[94] Karunathilake H, Hewage K, Sadiq R. Opportunities and challenges in energy demand reduction for Canadian residential sector: A review. Renewable and Sustainable Energy Reviews 2018; 82:2005–16. doi:10.1016/j.rser.2017.07.021.

[95] Dembo A, Khaddad F, Fung AS. Least-cost upgrade solutions to achieve improved energy efficiency standards for residential new housing in Canada. ASHRAE Transactions 2013; 119.

[96] Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings 2012;55:889–902. doi:10.1016/j.enbuild.2012.08.018.

[97] Leung BCM. Greening existing buildings [GEB] strategies. Energy Reports 2018; 4:159–206. doi:10.1016/j.egyr.2018.01.003.

[98] Jaffe AB, Newell RG, Stavins RN. Environmental policy and technological change. Environmental and Resource Economics 2002;22:41–70. doi:10.1023/A:1015519401088.

[99] Rivers N, Jaccard M. Choice of environmental policy in the presence of learning by doing. Energy Economics 2006; 28:223–42. doi:10.1016/j.eneco.2006.01.002.

[100] Wen Y. Modelling Emission Allowance Prices. University of Duisburg-Essen, 2017.

[101] Whitten S, Bueren M Van, Symposium DC-A, 2003 undefined. An overview of market-based instruments and environmental policy in Australia. AARES Symposium, 2003.

[102] Cairns S, Clarke A, Zhou Y, Thivierge V. Sustainability Alignment Manual (SAM): Using Market-Based Instruments to Accelerate Sustainability Progress at the Local Level. Ottawa and Waterloo: 2015.

[103] Zhou Y. Implementing Sustainable Community Plans through Market-based Instruments. University of Waterloo, 2015.

[104] Stavins RN. Experience with Market-Based Environmental Policy Instruments, 2003, p. 355–435. doi:10.1016/S1574-0099(03)01014-3.

[105] Rademaekers K, Laan J van der, Smith M, Breugel C van, Pollitt H. The role of market-based instruments in achieving a resource efficient economy. Rotterdam: 2011.

[106] Khattab AS. The impact of reducing energy subsidies on energy intensive industries in Egypt. The Egyptian Economy: Current Challenges and Future Prospects 2008:263–6.

[107] The Atmospheric Fund. Energy Efficiency Financing Tools for the Canadian Context. Toronto: 2017.

[108] de T'Serclaes P. Financing energy efficient homes-Existing policy responses to financial barriers. Paris, France: 2007.

[109] Energy Efficient Green Home Rebate on Mortgage Loan Insurance. CMHC 2017. https://www.cmhc-schl.gc.ca/en/buying/mortgage-loan-insurance-for-consumers/cmhc-energy-efficient-housing-made-more-affordable-with-mortgage-loan-insurance (accessed August 23, 2018).

[110] RBC Energy Saver Loan. RBC Royal Bank 2018. http://www.rbcroyalbank.com/personal-loans/energy-saver-loan.html?topnavclick=true (accessed August 29, 2018).

[111] Home Energy Loan Program. Efficiency PEI 2018. https://www.toronto.ca/services-payments/water-environment/environmental-grants-incentives-2/home-energy-loan-program-help/ (accessed August 23, 2018).

[112] ENERGY STAR® Loan Program. SaskEnergy 2018. http://www.saskenergy.com/Residential/appliancefinancing.asp (accessed August 23, 2018).

[113] Energy Retrofit Loans 2018. https://www.toronto.ca/services-payments/water-environment/environmental-grants-incentives-2/energy-retrofit-loans/ (accessed August 23, 2018).

[114] Power Smart Residential Loan. Manitoba Hydro 2018. https://www.hydro.mb.ca/your_home/power_smart/residential_loan/ (accessed August 23, 2018).

[115] EMMC. Financing Energy Efficiency Retrofits in the Built Environment. Energy and Mines Ministers' Conference, ISBN 978-0-660-05820-7; 2016.

[116] Kempa K, Moslener U. Climate policy with the chequebook - An economic analysis of climate investment support. Economics of Energy and Environmental Policy 2017;6:111–29. doi:10.5547/2160-5890.6.1.kkem.

[117] Tasdoven H, Fiedler BA, Garayev V. Improving electricity efficiency in Turkey by addressing illegal electricity consumption: A governance approach. Energy Policy 2012;43:226–34. doi:10.1016/j.enpol.2011.12.059.

[118] Revilla M, Laarni D. Cross-country econometric study on the impact of fiscal incentives on FDI (No. 2016-17). 2016.

[119] Boyle S. DSM progress and lessons in the global context. Energy Policy 1996;24:345–59. doi:10.1016/0301-4215(95)00142-5.

[120] Vera S, Sauma E. Does a carbon tax make sense in countries with still a high potential for energy efficiency? Comparison between the reducing-emissions effects of carbon tax and energy efficiency measures in the Chilean case. Energy 2015;88:478–88. doi:10.1016/j.energy.2015.05.067.

[121] Adamaley M, Barbara T, Excellence R, Scholarship N, Rhomberg B, Gifford JS, et al. Green building incentives: A review. Renewable and Sustainable Energy Reviews 2016;1:1–8. doi:10.1016/j.rser.2016.01.028.

[122] Tinker A, Kreuter U, Burt R, Bame S. Green Construction: Contractor Motivation and Trends in Austin, Texas. Journal of Green Building 2006;1:118–34. doi:10.3992/jgb.1.2.118.

[123] Yang J, Xu C. Rethinking Incentive Policy for Building Energy Efficiency. Advanced Materials Research 2011;374–377:195–8. doi:10.4028/www.scientific.net/AMR.374-377.195.

[124] Ministry of Community Services Government of BC. Revitalization Tax Exemptions: A Primer on the Provisions in the Community Charter 2008.

[125] Revitalization Tax Exemptions (RTEs) n.d. http://www.toolkit.bc.ca/getting-max-exempting-tax (accessed January 28, 2020).

[126] RénoVert Tax Credit. Revenu Québec 2018. https://www.revenuquebec.ca/en/citizens/tax-credits/renovert-tax-credit/ (accessed August 25, 2018).

[127] ürge-Vorsatz D, Koeppel S, Mirasgedis S. Appraisal of policy instruments for reducing buildings' CO 2 emissions. Building Research & Information 2007; 35:458–77. doi:10.1080/09613210701327384.

[128] Hood I. Paper 4c: Green Residential Building in North America: The Benefits of a North American Strategy: A Perspective from Canada. 2008.

[129] Bond SA, Devine A. Incentivizing Green Single-Family Construction: Identifying Effective Government Policies and Their Features. Journal of Real Estate Finance and Economics 2016; 52:383–407. doi:10.1007/s11146-015-9525-0.

[130] NRCan. Grants and Financial Incentives 2017. http://www.nrcan.gc.ca/energy/funding/efficiency/4947 (accessed February 11, 2017).

[131] Transportation, Infrastructure and Energy. Government of Prince Edward Island 2018. https://www.princeedwardisland.ca/en/information/transportation-infrastructure-and-energy/energy-efficient-equipment-rebates (accessed August 27, 2018).

[132] Lee WL, Yik FWH. Framework for formulating a performance-based incentive-rebate scale for the demand-side-energy management scheme for commercial buildings in Hong Kong. Applied Energy 2002;73:139–66. doi:10.1016/S0306-2619(02)00075-2.

[133] Eide J, de Sisternes FJ, Herzog HJ, Webster MD. CO2 emission standards and investment in carbon capture. Energy Economics 2014;45:53–65. doi:10.1016/j.eneco.2014.06.005.

[134] Ghalwash T. Energy taxes as a signaling device: An empirical analysis of consumer preferences. Energy Policy 2007;35:29–38. doi:10.1016/j.enpol.2005.09.011.

[135] Tsai W-H, Lin S-J, Liu J-Y, Lin W-R, Lee K-C. Incorporating life cycle assessments into building project decision-making: An energy consumption and CO2 emission perspective. Energy 2011; 36:3022–9. doi:10.1016/j.energy.2011.02.046.

[136] Lee CF, Lin SJ, Lewis C. Analysis of the impacts of combining carbon taxation and emission trading on different industry sectors. Energy Policy 2008; 36:722–9. doi:10.1016/j.enpol.2007.10.025.

[137] Govt. BC. Carbon Tax Programs 2018. https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax/programs.

[138] Elgie S, McClay J. Policy Commentary/Commentaire BC's Carbon Tax Shift Is Working Well after Four Years (Attention Ottawa). Canadian Public Policy 2013; 39:S1–10. doi:10.3138/CPP.39.Supplement2.S1.

[139] Xiang D, Lawley C. The impact of British Columbia's carbon tax on residential natural gas consumption. Energy Economics 2019;80:206–18. doi:10.1016/j.eneco.2018.12.004.

[140] Government of Canada. Greenhouse Gas Pollution Pricing Act 2018.

[141] Liu L, Huang CZ, Huang G, Baetz B, Pittendrigh SM. How a carbon tax will affect an emission-intensive economy: A case study of the Province of Saskatchewan, Canada. Energy 2018;159:817–26. doi:10.1016/j.energy.2018.06.163.

[142] Gamtessa SF. An explanation of residential energy-efficiency retrofit behavior in Canada. Energy and Buildings 2013;57:155–64. doi:10.1016/j.enbuild.2012.11.006.

[143] Galatioto A, Ricciu R, Salem T, Kinab E. Energy and economic analysis on retrofit actions for Italian public historic buildings. Energy 2019; 58–66. doi:10.1016/j.energy.2019.03.167.

[144] Zhao T, Bell L, Horner MW, Sulik J, Zhang J. Consumer responses towards home energy financial incentives: A survey-based study. Energy Policy 2012; 47:291–7. doi:10.1016/j.enpol.2012.04.070.

[145] Enbridge Smart Savings. Enbridge Gas Distribution Inc 2018. https://enbridgesmartsavings.com/ (accessed August 27, 2018).

[146] NLHC | Housing Programs | HESP 2018. http://www.nlhc.nf.ca/programs/programsHesp.html (accessed August 25, 2018).

[147] NB Power 2018. https://www.nbpower.com/en/save-energy/residential/low-income-energy-savings-program/ (accessed August 28, 2018).

[148] Energy Efficiency Alberta 2018. https://www.efficiencyalberta.ca/business-non-profit-and-institutional/ (accessed August 25, 2018).

[149] Énergir | A Quebec company and an energy leader 2018. https://www.energir.com/en/ (accessed August 28, 2018).

[150] Gazifère 2018. https://www.gazifere.com/en/ (accessed August 28, 2018).

[151] Residential-savings & rebates. BCHydro 2018. https://www.bchydro.com/powersmart/residential/savings-and-rebates/current-rebates-buy-backs/home-renovation-rebates.html (accessed August 27, 2018).

[152] Rebates & offers. FortisBC 2018. https://www.fortisbc.com/Rebates/RebatesOffers/Pages/default.aspx (accessed August 27, 2018).

[153] Manitoba Hydro Electric Energy and Natural Gas 2018. https://www.hydro.mb.ca/ (accessed August 27, 2018).

[154] Mastropietro P, Rodilla P, Batlle C. Emergency Measures to Protect Energy Consumers During the Covid-19 Pandemic: Global Review and Critical Analysis 2020.

[155] Martin A, Markhvida M, Hallegatte S, Walsh B. Socio-Economic Impacts of COVID-19 on Household Consumption and Poverty 2020. doi:2005.05945, arXiv.org.

[156] Dubois M, Allacker K. Energy savings from housing: Ineffective renovation subsidies vs efficient demolition and reconstruction incentives. Energy Policy 2015; 86:697–704.

[157] Save Money & Energy. Union Gas 2018. https://www.uniongas.com/residential/save-money-energy/home-reno (accessed August 27, 2018).

[158] Jeyakumar B, Hastings-Simon S. Capturing the Benefits of Energy Efficiency for Non-Profit Organizations. Calgary, Canada: 2016.

[159] Ozog S. Towards First Nations energy self-sufficiency: Analyzing the renewable energy partnership between T'sou-ke Nation and Skidegate Band. University of Northern British Columbia, 2012.

[160] Curtin J, McInerney C, Johannsdottir L. How can financial incentives promote local ownership of onshore wind and solar projects? Case study evidence from Germany, Denmark, the UK and Ontario. Local Economy: The Journal of the Local Economy Policy Unit 2018; 33:40–62. doi:10.1177/0269094217751868.

[161] Hydro One. First Nations Conservation Program 2020. https://www.hydroone.com/saving-money-and-energy/residential/first-nations-conservation-program.

[162] Manitoba Hydro. Indigenous Communities and energy efficiency 2020. https://www.hydro.mb.ca/programs/indigenous_communities/.

[163] Business & Industry. FortisBC 2018. https://www.fortisbc.com/Rebates/RebatesOffers/RefrigerationEquipmentRebates/Pages/default.aspx (accessed August 27, 2018).

[164] Hope AJ, Booth A. Attitudes and behaviours of private sector landlords towards the energy efficiency of tenanted homes. Energy Policy 2014; 75:369–78. doi:10.1016/j.enpol.2014.09.018.

[165] Stone W, Sharam A, Wiesel I, Ralston L, Markkanen S, James A. Accessing and sustaining private rental tenancies: critical life events, housing shocks and insurances-AHURI Final Report, 259. 2015.

[166] Wrigley K, Crawford RH. Identifying policy solutions for improving the energy efficiency of rental properties. Energy Policy 2017; 108:369–78. doi:10.1016/j.enpol.2017.06.009.

[167] Gillingham K, Harding M, Rapson D. Split Incentives in Residential Energy Consumption. The Energy Journal 2012; 33:37–62.

[168] Charlier D. Energy efficiency investments in the context of split incentives among French households. Energy Policy 2015; 87:465–79. doi:10.1016/j.enpol.2015.09.005.

[169] Instone L, Mee KJ, Palmer J, Williams M, Vaughan N. Climate change adaptation in the rental sector. Applied Studies in Climate Adaptation, Chichester, West Sussex: John Wiley & Sons; 2015, p. 372–9.

[170] Wrigley K, Crawford RH. Bridging the gap: energy efficiency improvements for rental properties. In Living and Learning: Research for a Better Built Environment. 49th International Conference of the Architectural Science Association, Melbourne, Australia.: 2015, p. 322–31.

[171] Phillips Y. Landlords versus tenants: Information asymmetry and mismatched preferences for home energy efficiency. Energy Policy 2012; 45:112–21. doi:10.1016/j.enpol.2012.01.067.

[172] Touchie M, Pressnail K, Tzekova E. Assessing potential energy retrofits of multi-unit residential buildings in the Greater Toronto area. 14th Canadian Conference on Building Science and Technology, 2014.

[173] Gurgun AP, Polat G, Bayhan HG, Damci A. Financial and economical risks impacting cost of LEED certified projects. Ninth International Structural Engineering and Construction Conference Valencia, Spain, July 24-July 29, 2017., ISEC Press; 2017. doi: 10.14455/ISEC.res.2017.208.

[174] Green Heat. Efficiency Nova Scotia 2018. https://www.efficiencyns.ca/service/home-heating/ (accessed August 25, 2018).

[175] City of Medicine Hat 2018. https://www.medicinehat.ca/government/departments/utility-sustainability/hat-smart/rebates/air-sealing (accessed August 25, 2018).

[176] Change Homes for Climate. City of Edmonton 2018. http://ace.edmonton.ca/energuide/ (accessed August 27, 2018).

[177] Govt. BC. BC Energy Step Code - Province of British Columbia 2017. https://www2.gov.bc.ca/gov/content/industry/construction-industry/building-codes-standards/energy-efficiency/energy-step-code (accessed October 29, 2017).

[178] Fertel C, Bahn O, Vaillancourt K, Waaub JP. Canadian energy and climate policies: A SWOT analysis in search of federal/provincial coherence. Energy Policy 2013; 63:1139–50. doi:10.1016/j.enpol.2013.09.057.

[179] Parker P, Rowlands IH. City partners maintain climate change action despite national cuts: Residential energy efficiency programme valued at local level. Local Environment 2007; 12:505–17. doi:10.1080/13549830701656853.

[180] Rana IA, Routray JK, Younas ZI. Spatiotemporal dynamics of development inequalities in Lahore City Region, Pakistan. Cities 2020; 96. doi:10.1016/j.cities.2019.102418.

[181] Reynolds M. Green building financial incentives. Ecohome Resources for Sustainable Housing n.d. http://www.ecohome.net/guide/green-building-financial-incentives (accessed February 5, 2017).

[182] Commercial Energy Conservation and Efficiency Program. Arctic Energy Alliance 2018. http://aea.nt.ca/programs/commercial-energy-conservation-and-efficiency-program (accessed July 6, 2017).

[183] Vergragt PJ, Brown HS. The challenge of energy retrofitting the residential housing stock: grassroots innovations and socio-technical system change in Worcester, MA. Technology Analysis & Strategic Management 2012;24:407–20. doi:10.1080/09537325.2012.663964.

[184] Boehm A. The Role of Government in Creating Green Buildings 2010:1–30.

[185] Eco-Roof Incentive Program 2018. https://www.toronto.ca/services-payments/water-environment/environmental-grants-incentives-2/green-your-roof/ (accessed August 25, 2018).

[186] Ishaq S, Hewage K, Farooq S, Sadiq R. State of provincial regulations and guidelines to promote low impact development (LID) alternatives across Canada: Content analysis and comparative assessment. Journal of Environmental Management 2019; 235:389–402. doi:10.1016/j.jenvman.2019.01.074.

[187] Thollander P, Dotzauer E. An energy efficiency program for Swedish industrial small- and medium-sized enterprises. Journal of Cleaner Production 2010 ;18:1339–46. doi:10.1016/j.jclepro.2010.04.020.

[188] Mundaca L, Neij L, Worrell E, McNeil M. Evaluating Energy Efficiency Policies with Energy-Economy Models. Annual Review of Environment and Resources 2010; 35:305–44. doi:10.1146/annurev-environ-052810-164840.

[189] Geller H, Attali S. The experience with energy efficiency policies and programmes in IEA countries. Learning from the Critics Paris: IEA IEA Information Paper 2005.

[190] Maher J. Evaluating the Cost-Effectiveness of Rebate Programs for Residential Energy-Efficiency Retrofits. Annual Meeting, August 4-6, 2013, Washington, DC (No. 150569). Agricultural and Applied Economics Association., Washington, DC: Agricultural and Applied Economics Association.; 2013.

[191] Lang C, Siler M. Engineering estimates versus impact evaluation of energy efficiency projects: Regression discontinuity evidence from a case study. Energy Policy 2013; 61:360–70. doi:10.1016/j.enpol.2013.06.122.

[192] Papineau M. Setting the standard? A framework for evaluating the cost-effectiveness of building energy standards. Energy Economics 2017; 64:63–76. doi:10.1016/j.eneco.2017.02.011.

[193] Higgins A, McNamara C, Foliente G. Modelling future uptake of solar photo-voltaics and water heaters under different government incentives. Technological Forecasting and Social Change 2014; 83:142–55. doi:10.1016/j.techfore.2013.07.006.

[194] Li X, Clark CD, Jensen KL, Yen ST. The Effect of Mail-in Utility Rebates on Willingness-to-Pay for ENERGY STAR(R) Certified Refrigerators. Environmental and Resource Economics 2016; 63:1–23. doi:10.1007/s10640-014-9833-5.

[195] Alberini A, Bigano A, Boeri M. Looking for free riding: energy efficiency incentives and Italian homeowners. Energy Efficiency 2014;7:571–90. doi:10.1007/s12053-013-9241-7.

[196] Guo F, Pachauri S, Cofala J. Cost-effective subsidy incentives for room air conditioners in China: An analysis based on a McFadden-type discrete choice model. Energy Policy 2017;110:375–85. doi:10.1016/j.enpol.2017.08.039.

[197] Li H, Bao Q, Ren X, Xie Y, Ren J, Yang Y. Reducing rebound effect through fossil subsidies reform: A comprehensive evaluation in China. Journal of Cleaner Production 2017; 141:305–14. doi:10.1016/j.jclepro.2016.09.108.

[198] Nauleau M-L. Free-riding on tax credits for home insulation in France: An econometric assessment using panel data. Energy Economics 2014; 46:78–92. doi:10.1016/j.eneco.2014.08.011.

[199] Li K, Lin B. Impact of energy conservation policies on the green productivity in China's manufacturing sector: Evidence from a three-stage DEA model. Applied Energy 2016; 168:351–63. doi:10.1016/j.apenergy.2016.01.104.

[200] Lu B, Du X, Huang S. The economic and environmental implications of wastewater management policy in China: From the LCA perspective. Journal of Cleaner Production 2017;142:3544–57. doi:10.1016/j.jclepro.2016.10.113.

[201] Li K, Zhang T. A novel grey forecasting model and its application in forecasting the energy consumption in Shanghai. Energy Systems 2019. doi:10.1007/s12667-019-00344-0.

[202] Mundaca L;, Neij L, Mundaca L. A Meta-Analysis of Bottom-Up Ex-Ante Energy Efficiency Policy Evaluation Studies 2010.

[203] Jaccard M, Dennis M. Estimating home energy decision parameters for a hybrid energy—economy policy model. Environmental Modeling & Assessment 2006; 11:91–100. doi:10.1007/s10666-005-9036-0.

[204] Heaps C. Long range Energy Alternatives Planning System an Introduction to LEAP 2008.

[205] Schulz TF, Kypreos S, Barreto L, Wokaun A. Intermediate steps towards the 2000W society in Switzerland: An energy–economic scenario analysis. Energy Policy 2008; 36:1303–17. doi:10.1016/j.enpol.2007.12.006.

[206] EIA. Integrating Module of the National Energy Modeling System: Model Documentation 2013 2013.

[207] Vergragt PJ, Quist J. Backcasting for sustainability: Introduction to the special issue. Technological Forecasting and Social Change 2011; 78:747–55. doi:10.1016/j.techfore.2011.03.010.

[208] Svenfelt Å, Engström R, Svane Ö. Decreasing energy use in buildings by 50% by 2050 — A backcasting study using stakeholder groups. Technological Forecasting and Social Change 2011; 78:785–96. doi:10.1016/j.techfore.2010.09.005.

[209] Boermans T, Bettgenhäuser K, Hermelink A, Schimschar S. Cost optimal building performance requirements. Stockholm: 2011.

[210] Sabatier PA. Top-Down and Bottom-Up Approaches to Implementation Research: A Critical Analysis and Suggested Synthesis. Journal of Public Policy 1986; 6:21–48. doi:10.1017/S0143814X00003846.

[211] Koopmans CC, Te Velde DW. Bridging the energy efficiency gap: Using bottom-up information in a top-down energy demand model. Energy Economics 2001; 23:57–75. doi:10.1016/S0140-9883(00)00054-2.

[212] Markandya A, Ortiz RA, Mudgal S, Tinetti B. Analysis of tax incentives for energy-efficient durables in the EU. Energy Policy 2009; 37:5662–74. doi:10.1016/j.enpol.2009.08.031.

[213] Harmelink M, Joosen S, Blok K. The theory-based policy evaluation method applied to the ex-post evaluation of climate change policies in the built environment in the Netherlands. ECEEE, 2005.

[214] Hou J, Liu Y, Wu Y, Zhou N, Feng W. Comparative study of commercial building energy-efficiency retrofit policies in four pilot cities in China. Energy Policy 2016; 88:204–15. doi:10.1016/j.enpol.2015.10.016.

[215] Wang Z, Wang X, Guo D. Policy implications of the purchasing intentions towards energy-efficient appliances among China's urban residents: Do subsidies work? Energy Policy 2017; 102:430–9. doi:10.1016/j.enpol.2016.12.049.

[216] Amstalden RW, Kost M, Nathani C, Imboden DM. Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and

energy price expectations. Energy Policy 2007;35:1819–29. doi:10.1016/j.enpol.2006.05.018.

[217] Cho Y, Koo Y, Huh S-Y, Lee M. Evaluation of a consumer incentive program for an energy-efficient product in South Korea. Energy Efficiency 2015; 8:745–57. doi:10.1007/s12053-014-9319-x.

[218] Rivers N, Shiell L. Free riding on energy efficiency subsidies: The case of natural gas furnaces in Canada. Energy Journal 2016; 37:239–66. doi:10.5547/01956574.37.4.nriv.

[219] Yushchenko A, Patel MK. Cost-effectiveness of energy efficiency programs: How to better understand and improve from multiple stakeholder perspectives? Energy Policy 2017; 108:538–50. doi:10.1016/j.enpol.2017.06.015.

[220] Roy AM, Seraspe RL, Desai T. Using Building Size to Optimize Electric Utility Energy Efficiency Incentives. Strategic Planning for Energy and the Environment 2016; 36:18–31. doi:10.1080/10485236.2016.11735276.

[221] Vringer K, Middelkoop M van, Hoogervorst N. Saving energy is not easy: An impact assessment of Dutch policy to reduce the energy requirements of buildings. Energy Policy 2016; 93:23–32.

[222] Suerkemper F, Thomas S, Osso D, Baudry P. Cost-effectiveness of energy efficiency programmes—evaluating the impacts of a regional programme in France. Energy Efficiency 2012; 5:121–35. doi:10.1007/s12053-011-9112-z.

[223] Joelsson A, Gustavsson L. Perspectives on implementing energy efficiency in existing Swedish detached houses. Energy Policy 2008; 36:84–96. doi:10.1016/j.enpol.2007.08.021.

[224] Carter T, Keeler A. Life-cycle cost–benefit analysis of extensive vegetated roof systems. Journal of Environmental Management 2008; 87:350–63. doi:10.1016/j.jenvman.2007.01.024.

[225] Olsthoorn M, Schleich J, Gassmann X, Faure C. Free riding and rebates for residential energy efficiency upgrades: A multi-country contingent valuation experiment. Energy Economics 2017; 68:33–44. doi:10.1016/j.eneco.2018.01.007.

[226] Ferrara M, Monetti V, Fabrizio E. Cost-Optimal Analysis for Nearly Zero Energy Buildings Design and Optimization: A Critical Review. Energie 2018; 11:1–32. doi:10.3390/en11061478.

[227] Kuusk K, Kalamees T. Retrofit cost-effectiveness: Estonian apartment buildings. Building Research & Information 2016; 44:920–34. doi:10.1080/09613218.2016.1103117.

[228] Koeppel S, Ürge-Vorsatz D. Assessment of policy instruments for reducing greenhouse gas emissions from buildings. Budapest: 2007. doi:9789638771407.

[229] Jurušs M, Brizga J. Assessment of the Environmental Tax System in Latvia. NISPAcee Journal of Public Administration and Policy 2017; 10:135–54. doi:10.1515/nispa-2017-0015.

[230] Galarraga I, Abadie LM, Ansuategi A. Efficiency, effectiveness and implementation feasibility of energy efficiency rebates: The “Renove” plan in Spain. Energy Economics 2013; 40:S98–107. doi:10.1016/j.eneco.2013.09.012.

[231] Ferreira M, Almeida M, Rodrigues A. Cost-optimal energy efficiency levels are the first step in achieving cost effective renovation in residential buildings with a nearly-zero energy target. Energy and Buildings 2016; 133:724–37. doi:10.1016/j.enbuild.2016.10.017.

[232] Martinaitis V, Rogoža A, Bikmanien I. Criterion to evaluate the “twofold benefit” of the renovation of buildings and their elements. Energy and Buildings 2004; 36:3–8. doi:10.1016/S0378-7788(03)00054-9.

[233] Tommerup H, Svendsen S. Energy savings in Danish residential building stock. Energy and Buildings 2006; 38:618–26. doi:10.1016/j.enbuild.2005.08.017.

[234] Dylewski R, Adamczyk J. Study on ecological cost-effectiveness for the thermal insulation of building external vertical walls in Poland. Journal of Cleaner Production 2016;133:467–78. doi:10.1016/j.jclepro.2016.05.155.

[235] IPCC. Environmental effectiveness - AR4 WGIII Chapter 13: Policies, instruments, and co-operative arrangements. 2007.

[236] Higgins A, Foliente G, McNamara C. Modelling intervention options to reduce GHG emissions in housing stock — A diffusion approach. Technological Forecasting and Social Change 2011; 78:621–34. doi:10.1016/j.techfore.2010.12.003.

[237] Yao X-L, Liu Y, Yan X. A quantile approach to assess the effectiveness of the subsidy policy for energy-efficient home appliances: Evidence from Rizhao, China. Energy Policy 2014; 73:512–8. doi:10.1016/j.enpol.2014.06.010.

[238] Zamfirescu C, Dincer I, Stern M, Wagar WR. Exergetic, environmental and economic analyses of small-capacity concentrated solar-driven heat engines for power and heat cogeneration. International Journal of Energy Research 2012; 36:397–408. doi:10.1002/er.1811.

[239] Beccali M. A survey on energy performance of the non- residential public building stock in Southern Italy ; toward a decision support tool for refurbishment actions. 2016.

[240] Vedung E. Public Policy and Program Evaluation. Routledge; 1997.

[241] Lin W-M, Chang K-C, Chung K-M. Economic aspects for solar thermal application in Taiwan. Sustainable Cities and Society 2016; 26:354–63. doi:10.1016/j.scs.2016.07.008.

[242] Lee M, Hong T, Koo C, Kim C-J. A break-even analysis and impact analysis of residential solar photovoltaic systems considering state solar incentives. Technological and Economic Development of Economy 2017:1–25. doi:10.3846/20294913.2016.1212745.

[243] Howarth RB, Haddad BM, Paton B. The economics of energy effciency : insights from voluntary participation programs. Energy Policy 2000; 28:477–86. doi:10.1016/S0301-4215(00)00026-4.

[244] Robinson JF, Foxon TJ, Taylor PG. Performance gap analysis case study of a non-domestic building. Proceedings of the Institution of Civil Engineers. Engineering sustainability, vol. 169, 2016. doi:10.1680/ensu.14.00055.

[245] Melvin J. The split incentives energy efficiency problem: Evidence of underinvestment by landlords. Energy Policy 2018; 115:342–52. doi:10.1016/j.enpol.2017.11.069.

[246] Wiese C, Larsen A, Pade L-L. Interaction effects of energy efficiency policies: a review. Energy Efficiency 2018. doi:10.1007/s12053-018-9659-z.

[247] Boonekamp P. Actual interaction effects between policy measures for energy efficiency—A qualitative matrix method and quantitative simulation results for households. Energy 2006; 31:2848–73. doi:10.1016/j.energy.2006.01.004.

[248] Child R, Langniss O, Klink J, Gaudioso D. Interactions of white certificates with other policy instruments in Europe. Energy Efficiency 2008;1:283–95. doi:10.1007/s12053-008-9025-7.

[249] Rosenow J, Fawcett T, Eyre N, Oikonomou V. Energy saving policies and energy efficiency obligation schemes. D5. 1 Combining of Energy Efficiency Obligations and alternative policies. 2015.

[250] Matviichuk N, Shulyk Y, Shmatkovska T. Financial incentives to energy saving in the housing sector of Ukraine. Scientific Bulletin of Polissia 2017; 2:32–9.

[251] Brotman BA. The feasibility of medical office building green upgrades from an owner/lessor perspective. Journal of Property Investment & Finance 2016; 34:375–86. doi:/10.1108/MRR-09-2015-0216.

[252] Kerr N, Winskel M. Household investment in home energy retrofit: A review of the evidence on effective public policy design for privately owned homes. Renewable and Sustainable Energy Reviews 2020;123. doi:10.1016/j.rser.2020.109778.

[253] Murphy L, Meier F. Waking a Sleeping Giant: Policy Tools to Improve the Energy Performance of the Existing Housing Stock in The Netherlands 2011.

[254] Jollands N, Waide P, Ellis M, Onoda T, Laustsen J, Tanaka K, et al. The 25 IEA energy efficiency policy recommendations to the G8 Gleneagles Plan of Action. Energy Policy 2010; 38:6409–18. doi:10.1016/j.enpol.2009.11.090.

[255] Kelly G. Sustainability at home: Policy measures for energy-efficient appliances. Renewable and Sustainable Energy Reviews 2012; 16:6851–60. doi:10.1016/j.rser.2012.08.003.

[256] Hausman JA. Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables. The Bell Journal of Economics 1979; 10:33. doi:10.2307/3003318.

[257] Houston DA. Implicit Discount Rates and the Purchase of Untried, Energy-Saving Durable Goods. Journal of Consumer Research 1983; 10:236. doi:10.1086/208962.

[258] Hor K, Rahmat MK. Analysis and recommendations for building energy efficiency financing in Malaysia. Energy Efficiency 2018; 11:79–95. doi:10.1007/s12053-017-9551-2.

[259] Trencher G, van der Heijden J. Instrument interactions and relationships in policy mixes: Achieving complementarity in building energy efficiency policies in New York, Sydney and Tokyo. Energy Research and Social Science 2019; 54:34–45. doi:10.1016/j.erss.2019.02.023.

[260] Brewer GD, Stern PC. Decision making for the environment: Social and behavioral science research priorities. Washington, DC: National Academies Press; 2005.

[261] Wang X, Lin B. Impacts of residential electricity subsidy reform in China. Energy Efficiency 2017; 10:499–511. doi:10.1007/s12053-016-9466-3.

[262] Alberini A, Bigano A. How effective are energy-efficiency incentive programs? Evidence from Italian homeowners. Energy Economics 2015; 52:S76–85. doi:10.1016/j.eneco.2015.08.021.

[263] Rana A, Perera P, Ruparathna R, Karunathilake H, Hewage K, Alam MS, et al. Occupant-based energy upgrades selection for Canadian residential buildings based on field energy data and calibrated simulations. Journal of Cleaner Production 2020:122430. doi:10.1016/j.jclepro.2020.122430.

[264] Ebrahimigharehbaghi S, Qian QK, Meijer FM, Visscher HJ. Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: What drives and hinders their decision-making? Energy Policy 2019:546–61. doi:10.1016/j.enpol.2019.02.046.

[265] Eguaras-Martínez M, Vidaurre-Arbizu M, Martín-Gómez C. Simulation and evaluation of Building Information Modeling in a real pilot site. Applied Energy 2014; 114:475–84. doi:10.1016/j.apenergy.2013.09.047.

[266] Parker D, Mills E, Rainer L, Bourassa N, Homan G. Accuracy of the home energy saver energy calculation methodology. ACEEE Summer Study on Energy Efficiency in Buildings, 2012.

[267] Al-Mumin A, Khattab O, Sridhar G. Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences. Energy and Buildings 2003; 35:549–59. doi:10.1016/S0378-7788(02)00167-6.

[268] Gaetani I, Hoes P-J, Hensen JLM. Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy. Energy and Buildings 2016; 121:188–204. doi:10.1016/j.enbuild.2016.03.038.

[269] de Wilde P. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction 2014; 41:40–9. doi:10.1016/j.autcon.2014.02.009.

[270] Majcen D, Itard LCM, Visscher H. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. Energy Policy 2013; 54:125–36. doi:10.1016/j.enpol.2012.11.008.

[271] Motuziene V, Vilutiene T. Modelling the effect of the domestic occupancy profiles on predicted energy demand of the energy efficient house. Procedia Engineering, vol. 57, Elsevier Ltd; 2013, p. 798–807. doi:10.1016/j.proeng.2013.04.101.

[272] Rumeo ME. Evaluating the Field Performance of a Thermally-Retrofitted Historic Masonry Home Using a Nested Thermal Envelope Design. University of Toronto, 2019.

[273] Newsham GR, Donnelly CL. model of residential energy end-use in Canada: Using conditional demand analysis to suggest policy options for community energy planners. Energy Policy 2013; 59:133–42. doi:10.1016/j.enpol.2013.02.030.

[274] Cosar-Jorda P. A socio-technical evaluation of the impact of energy demand reduction measures in family homes. Loughborough University, 2018.

[275] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews 2009; 13:1819–35. doi:10.1016/j.rser.2008.09.033.

[276] Richardson I, Thomson M, Infield D, Clifford C. Domestic electricity use: A high-resolution energy demand model. Energy and Buildings 2010; 42:1878–87. doi:10.1016/j.enbuild.2010.05.023.

[277] Ridi A, Gisler C, Hennebert J. A Survey on Intrusive Load Monitoring for Appliance Recognition. 2014 22nd International Conference on Pattern Recognition, IEEE; 2014, p. 3702–7. doi:10.1109/ICPR.2014.636.

[278] NRCan. Tools for industry professionals | Natural Resources Canada 2019. https://www.nrcan.gc.ca/energy/efficiency/homes/20596#general (accessed March 19, 2019).

[279] Raftery P, Keane M, O'Donnell J. Calibrating whole building energy models: An evidence-based methodology. Energy and Buildings 2011; 43:2356–64. doi:10.1016/j.enbuild.2011.05.020.

[280] Yang Z, Becerik-Gerber B. A model calibration framework for simultaneous multi-level building energy simulation. Applied Energy 2015;149:415–31. doi:10.1016/j.apenergy.2015.03.048.

[281] Gucyeter B. Calibration of a building energy performance simulation model via monitoring data. Building Performance Analysis Conference and SimBuild, Chicago: ASHRAE and IBPSA-USA; 2018.

[282] ASHRAE. ASHRAE Guideline 14–2014: Measurement of Energy; Demand; and Water Savings. 2014.

[283] US-DOE. M&V guidelines: measurement and verification for federal energy projects version 3.0. 2008.

[284] IPMVP. IPMVP Committee and others. International performance measurement and verification protocol: concepts and options for determining energy and water savings. 2012.

[285] Warren JL. Development of an integrated life-cycle cost assessment model. Electronics and the Environment, 1994 ISEE 1994 1994:155–63. doi:10.1109/ISEE.1994.337306.

[286] Ruparathna R, Hewage K, Sadiq R. Rethinking investment planning and optimizing net zero emission buildings. Clean Technologies and Environmental Policy 2017; 19:1711–24. doi:10.1007/s10098-017-1359-4.

[287] McLeod P, Fay R. The cost effectiveness of housing thermal performance improvements in saving CO 2 -e. Architectural Science Review 2011; 54:117–23. doi:10.1080/00038628.2011.582370.

[288] Barkokebas DR, Chen Y, Yu H, Al-Hussein M. Achieving housing energy-efficiency requirements: Methodologies and impacts on housing construction cost and energy performance. Journal of Building Engineering 2019; 26:100874. doi:10.1016/j.jobe.2019.100874.

[289] Hesaraki B, Chen Y, Dias Ferreira R, Al-Hussein M. Energy code compliant house design for lowest lifecycle cost based on market-available technologies. Canadian Journal of Civil Engineering 2019; 46:308–21. doi:10.1139/cjce-2018-0237.

[290] Fuller SK, Petersen SR. Life-Cycle Costing Manual for the Federal Energy Management Program. NIST Handbook 135 1996:224. doi:10.1108/eb006413.

[291] Hasan A, Vuolle M, Sirén K. Minimisation of life cycle cost of a detached house using combined simulation and optimisation. Building and Environment 2008; 43:2022–34. doi:10.1016/j.buildenv.2007.12.003.

[292] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy and Buildings 2013; 56:189–203. doi:10.1016/j.enbuild.2012.08.023.

[293] Brander M. Greenhouse Gases, CO2, CO2e, and Carbon: What Do All These Terms Mean? 2012.

[294] Torcellini P, Pless S, Deru M, Crawley D. Zero energy buildings: a critical look at the definition. ACEEE Summer Study Pacific Grove, California: 2006.

[295] Asadi E, da Silva MG, Antunes CH, Dias L. Multi-objective optimization for building retrofit strategies: A model and an application. Energy and Buildings 2012;44:81–7. doi:10.1016/j.enbuild.2011.10.016.

[296] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—A review. Renewable and Sustainable Energy Reviews 2004; 8:365–81. doi:10.1016/j.rser.2003.12.007.

[297] El-Jamal G, Ghandour M, Ibrahim H. Application of multicriteria decision-methods for the selection of renewable energy sources, Lebanese case study. 2nd International Conference Efficient Building Design: Materials and HVAC Equipment Technologies, Beirut, Lebanon.: 2016.

[298] Kabir G, Sadiq R, Tesfamariam S. A review of multi-criteria decision-making methods for infrastructure management. Structure and Infrastructure Engineering 2014; 10:1176–210. doi:10.1080/15732479.2013.795978.

[299] Hwang C-L, Yoon K. Multiple attribute decision making: a state of the art survey. Lecture Notes in Economics and Mathematical Systems 186, 1981.

[300] Lee W-S, Lin L-C. Evaluating and ranking the energy performance of office building using technique for order preference by similarity to ideal solution. Applied Thermal Engineering 2011; 31:3521–5. doi:10.1016/j.applthermaleng.2011.07.005.

[301] Zagorskas J, Zavadskas EK, Turskis Z, Burinskienė M, Blumberga A, Blumberga D. Thermal insulation alternatives of historic brick buildings in Baltic Sea Region. Energy and Buildings 2014; 78:35–42. doi:10.1016/j.enbuild.2014.04.010.

[302] Wang E, Alp N, Shi J, Wang C, Zhang X, Chen H. Multi-criteria building energy performance benchmarking through variable clustering based compromise TOPSIS with objective entropy weighting. Energy 2017; 125:197–210. doi:10.1016/j.energy.2017.02.131.

[303] Perera P, Hewage K, Alam MS, Mèrida W, Sadiq R. Scenario-based economic and environmental analysis of clean energy incentives for households in Canada: Multi criteria decision making approach. Journal of Cleaner Production 2018; 198:170–86. doi:10.1016/j.jclepro.2018.07.014.

[304] CCTH. Canadian Centre for Housing Technology. Twin Research Houses 2016. http://www.ccht-cctr.gc.ca/eng/.

[305] STEP. The Archetype Sustainable Houses: Overview of Design and Monitoring Systems. Toronto: 2011.

[306] The Government of British Columbia. BC Building Code 2012 2020. http://free.bcpublications.ca/civix/content/public/bcbc2012/?xsl=/templates/browse.xsl.

[307] Statcan. Overview of household types, Canada, 2016 2017. https://www150.statcan.gc.ca/n1/daily-quotidien/170802/g-a001-eng.htm.

[308] Statistics Canada. Retirement age by class of worker, annual1. Table 14-10-0060-01 Retirement Age by Class of Worker, Annual 2020. doi:10.25318/1410006001-ENG.

[309] NRCan. HOT2000 Software Suite 2020.

[310] Mohazabieh, S.Z. Ghajarkhosravi M, Fung AS. Energy consumption and environmental impact assessment of the energy efficient houses in Toronto, Canada. Procedia Engineering 2015;118:1024–9. doi:10.1016/j.proeng.2015.08.544.

[311] Webster L, Bradford J, Sartor D, Shonder J, Atkin E, Dunnivant S, et al. M&V Guidelines: Measurement and Verification for Performance-Based Contracts_Version 4.0 2015.

[312] Clarke JA, Strachan P, Pernot C. An approach to the calibration of building energy simulation models. ASHRAE Transactions 1993; 1:917–27.

[313] Coakley D, Raftery P, Keane M. A review of methods to match building energy simulation models to measured data. Renewable and Sustainable Energy Reviews 2014; 37:123–41. doi:10.1016/j.rser.2014.05.007.

[314] RS Means Company. Building construction cost data. RS Means Company; 2016.

[315] ASHRAE. Economic Database in Support of ASHRAE 90.2 (Energy-Efficient Design of Low-Rise Residential Buildings) - 1481 RP 2009;2.

[316] Authentech Homes. Wilden Living Lab Project 2016:BOQS.

[317] Kirk SJ, Dell'Isola AJ. Life cycle costing for design professionals. 1995.

[318] IMF. International Monetary Fund 2016.

[319] Snodgrass K. Life-Cycle Cost Analysis for Buildings is easier than you thought. United States Department of Agriculture 2003:24.

[320] FortisBC. Your electricity rates 2017. https://www.fortisbc.com/Electricity/CustomerService/ForHomes/YourElectricityRates/Pages/default.aspx (accessed February 2, 2017).

[321] Kikuchi E, Bristow D, Kennedy CA. Evaluation of region-specific residential energy systems for GHG reductions: Case studies in Canadian cities. Energy Policy 2009;37:1257–66. doi:10.1016/j.enpol.2008.11.004.

[322] NEB. Canada's Renewable Power Landscape 2016 - Energy Market Analysis 2018. https://www.neb-one.gc.ca/nrg/sttstc/lctrct/rprt/2016cndrnwblpwr/prvnc/bc-eng.html (accessed June 24, 2019).

[323] BC Ministry of Environment. BC Best Practices Methodology for Quantifying Greenhouse Gas Emissions. Victoria 2014.

[324] Hansen KA. Seasonality of moves and duration of residence (No. 66) 1998.

[325] Wächter P. The usefulness of marginal CO2-e abatement cost curves in Austria. Energy Policy 2013; 61:1116–26. doi:10.1016/j.enpol.2013.06.125.

[326] Amirirad A, Kumar R, Fung AS. Performance characterization of an indoor air source heat pump water heater for residential applications in Canada. International Journal of Energy Research 2018; 42:1316–27. doi:10.1002/er.3932.

[327] Karytsas S, Choropanitis I. Barriers against and actions towards renewable energy technologies diffusion: A Principal Component Analysis for residential ground source heat pump (GSHP) systems. Renewable and Sustainable Energy Reviews 2017;78:252–71. doi:10.1016/j.rser.2017.04.060.

[328] McKitrick R, Aliakbari E. Rising Electricity Costs and Declining Employment in Ontario's Manufacturing Sector. 2017.

[329] Yohanis YG, Mondol JD, Wright A, Norton B. Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. Energy and Buildings 2008;40:1053–9. doi:10.1016/j.enbuild.2007.09.001.

[330] De Meester T, Marique A-F, De Herde A, Reiter S. Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe. Energy and Buildings 2013; 57:313–23. doi:10.1016/j.enbuild.2012.11.005.

[331] NRCan. Energy Efficiency in Canada: Report to parliament under the Energy Efficiency Act 2017-2018. 2019.

[332] Ingle A, Moezzi M, Lutzenhiser L, Diamond R. Better home energy audit modelling: Incorporating inhabitant behaviours. Building Research and Information 2014; 42:409–21. doi:10.1080/09613218.2014.890776.

[333] Government of Canada. Action for Seniors report. 2014.

[334] Marshall E, Steinberger JK, Dupont V, Foxon TJ. Combining energy efficiency measure approaches and occupancy patterns in building modelling in the UK residential context. Energy and Buildings 2016; 111:98–108. doi:10.1016/j.enbuild.2015.11.039.

[335] Rouleau J, Ramallo-González AP, Gosselin L, Blanchet P, Natarajan S. A unified probabilistic model for predicting occupancy, domestic hot water use and electricity use in residential buildings. Energy and Buildings 2019;202. doi:10.1016/j.enbuild.2019.109375.

[336] Poortinga W, Steg L, Vlek C, Wiersma G. Household preferences for energy-saving measures: A conjoint analysis. Journal of Economic Psychology 2003; 24:49–64. doi:10.1016/S0167-4870(02)00154-X.

[337] Guerra-Santin O. Behavioural Patterns and User Profiles related to energy consumption for heating. Energy and Buildings 2011; 43:2662–72. doi:10.1016/j.enbuild.2011.06.024.

[338] Hinson S. COVID-19 is changing residential electricity demand. Renewable Energy World 2020. https://www.renewableenergyworld.com/2020/04/09/covid-19-is-changing-residential-electricity-demand/.

[339] Rouleau J, Gosselin L. Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building. Applied Energy 2021;287. doi:10.1016/j.apenergy.2021.116565.

[340] Guyot K, Sawhill I V. Telecommuting will likely continue long after the pandemic. Brookings; April 06, 2020. Brookings 2020. https://www.brookings.edu/blog/up-front/2020/04/06/telecommuting-will-likely-continue-long-after-the-pandemic/ (accessed April 29, 2021).

[341] NRCan. Directory of Energy Efficiency and Alternative Energy Programs in Canada. National Energy Use Database 2020. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/policy_e/results.cfm?programtypes=4&regionaldeliveryid=11&attr=0 (accessed April 30, 2020).

[342] FortisBC. Rebates and offers-for homes 2020. https://www.fortisbc.com/rebates-and-energy-savings/rebates-and-offers?l=9ed1b561-afc0-4f6e-a816-d19343e0816d (accessed April 30, 2020).

[343] Environment and climate change Canada. National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada. Gatineau 2018.

[344] Bastos J, Batterman SA, Freire F. Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. Energy and Buildings 2014; 69:344–53. doi:10.1016/j.enbuild.2013.11.010.

[345] Myors P, O’Leary R, Helstroom R. Multi-unit residential building energy and peak demand study. Energy News 2005; 23:113–6.

[346] Maruejols L, Young D. Split incentives and energy efficiency in Canadian multi-family dwellings. Energy Policy 2011;39:3655–68. doi:10.1016/j.enpol.2011.03.072.

[347] Wang YM, Luo Y. On rank reversal in decision analysis. Mathematical and Computer Modelling 2009;49:1221–9. doi:10.1016/j.mcm.2008.06.019.

[348] Cooper RG. Winning with new products. Ivey Business Journal 2000; 64:54–60.

[349] Qaradaghi M, Deason JP. Analysis of MCDM methods output coherence in oil and gas portfolio prioritization. Journal of Petroleum Exploration and Production Technology 2018; 8:617–40. doi:10.1007/s13202-017-0344-0.

[350] Bhattacharya RK, Chatterjee N Das, Das K. Sub-basin prioritization for assessment of soil erosion susceptibility in Kangsabati, a plateau basin: A comparison between MCDM and SWAT models. Science of the Total Environment 2020;734. doi:10.1016/J.SCITOTENV.2020.139474.

[351] Biyik E, Kahraman A. A predictive control strategy for optimal management of peak load, thermal comfort, energy storage and renewables in multi-zone buildings. Journal of Building Engineering 2019; 25. doi:10.1016/j.jobe.2019.100826.

[352] Huang Z, Zhang Y, Lu Y, Wang W, Chen D, Wang C, et al. Cost Allocation Model for Net-Zero Energy Buildings under Community-Based Reward Penalty Mechanism. Environmental and Climate Technologies 2019;23:293–307. doi:10.2478/rtuect-2019-0096.

[353] He BJ. Towards the next generation of green building for urban heat island mitigation: Zero UHI impact building. Sustainable Cities and Society 2019;50. doi:10.1016/j.scs.2019.101647.

[354] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy and Buildings 2008;40:394–8. doi:10.1016/j.enbuild.2007.03.007.

[355] Sekar A, Williams E, Hittinger E, Chen R. How behavioral and geographic heterogeneity affects economic and environmental benefits of efficient appliances. Energy Policy 2019; 125:537–47. doi:10.1016/j.enpol.2018.10.035.

[356] Galvin R. Thermal upgrades of existing homes in Germany: The building code, subsidies, and economic efficiency. Energy and Buildings 2010; 42:834–44. doi:10.1016/j.enbuild.2009.12.004.

[357] Mauro GM, Hamdy M, Vanoli GP, Bianco N, Hensen JLM. A new methodology for investigating the cost-optimality of energy retrofitting a building category. Energy and Buildings 2015; 107:456–78. doi:10.1016/j.enbuild.2015.08.044.

[358] Jin Q, Overend M, Thompson P. Towards productivity indicators for performance-based façade design in commercial buildings. Building and Environment 2012;57:271–81. doi:10.1016/j.buildenv.2012.05.009.

[359] Pan W, Garmston H. Compliance with building energy regulations for new-build dwellings. Energy 2012; 48:11–22. doi:10.1016/j.energy.2012.06.048.

[360] State of California. Building Energy Efficiency Standards - Title 24 2020. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards.

[361] Bartlett R, Halverson MA, Shankle DL. Understanding building energy codes and standards (No. PNNL-14235). Pacific Northwest National Lab.(PNNL), Richland, WA (United States). Richland, Washington 99352: 2003.

[362] Kraljevska E. Estimated benefits of achieving passivhaus and net zero energy standards in the Region of Waterloo Residential Sector and the barriers and drivers to achieve them. University of Waterloo, 2014.

[363] Williams J. Zero-carbon homes: a road map. Routledge; 2013.

[364] Wills AD. On the Modelling and Analysis of Converting Existing Canadian Residential Communities to Net-Zero Energy. Carleton University, 2018.

[365] New York State. NYStretch Energy Code-2020 2020. https://www.nyserda.ny.gov/All-Programs/Programs/Energy-Code-Training/NYStretch-Energy-Code-2020 (accessed January 25, 2021).

[366] Yip A, Richman R. Reducing Ontario’s new single-family residential heating energy consumption by 80% by 2035: Economic analysis of a tiered framework of performance targets. Canadian Journal of Civil Engineering 2015; 42:1135–45. doi:10.1139/cjce-2015-0234.

[367] Hlavinka AN, Mjelde JW, Dharmasena S, Holland C. Forecasting the adoption of residential ductless heat pumps. Energy Economics 2016; 54:60–7. doi:10.1016/j.eneco.2015.11.020.

[368] Zhang J, Cho H, Luck R, Mago PJ. Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US. Applied Energy 2018; 212:895–908. doi:10.1016/j.apenergy.2017.12.091.

[369] Ascione F. A Methodology to Assess and Improve the Impact of Public Energy Policies for Retrofitting the Building Stock: Application to Italian Office Buildings. International Journal of Heat and Technology 2016; 34:S277–86. doi:10.18280/ijht.34S213.

[370] Zhang J, Knizley A, Cho H. Investigation of existing financial incentive policies for solar photovoltaic systems in U.S. regions. AIMS Energy 2017; 5:974–96. doi:10.3934/ENERGY.2017.6.974.

[371] Yushchenko A, Patel MK. Cost-effectiveness of energy efficiency programs: How to better understand and improve from multiple stakeholder perspectives? Energy Policy 2017; 108:538–50. doi:10.1016/j.enpol.2017.06.015.

[372] Boza-Kiss B, Moles-Grueso S, Urge-Vorsatz D. Evaluating policy instruments to foster energy efficiency for the sustainable transformation of buildings. Current Opinion in Environmental Sustainability 2013; 5:163–76. doi:10.1016/j.cosust.2013.04.002.

[373] Penna P, Prada A, Cappelletti F, Gasparella A. Multi-objective optimization for existing buildings retrofitting under government subsidization. Science and Technology for the Built Environment 2015; 21:847–61. doi:10.1080/23744731.2015.1028867.

[374] Shah SAA, Longsheng C. New environmental performance index for measuring sector-wise environmental performance: a case study of major economic sectors in Pakistan. Environmental Science and Pollution Research 2020; 27:41787–802. doi:10.1007/s11356-020-10145-z.

[375] Nasiri F, Huang G. A fuzzy decision aid model for environmental performance assessment in waste recycling. Environmental Modelling and Software 2008; 23:677–89. doi:10.1016/j.envsoft.2007.04.009.

[376] Li MJ, Tao WQ. Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. Applied Energy 2017; 187:203–15. doi:10.1016/j.apenergy.2016.11.039.

[377] Nasiri F, Maqsood I, Huang G, Fuller N. Water quality index: A fuzzy river-pollution decision support expert system. Journal of Water Resources Planning and Management 2007; 133:95–105. doi:10.1061/_ASCE0733-9496_2007133:2_95.

[378] Frappé-Sénéclauze T-P. Is B.C.'s Energy Step Code a Blueprint for Canada? SABMagazine 2018:21–3.

[379] Cheslak K. Implementing building performance standards: Consistency is key. New Buildigns Institute (Nbi) 2020. https://newbuildings.org/implementing-building-performance-standards-consistency-is-key/.

[380] Corgnati SP, Fabrizio E, Filippi M, Monetti V. Reference buildings for cost optimal analysis: Method of definition and application. Applied Energy 2013; 102:983–93. doi:10.1016/j.apenergy.2012.06.001.

[381] Zakula T, Bagaric M, Ferdelji N, Milovanovic B, Mudrinic S, Ritosa K. Comparison of dynamic simulations and the ISO 52016 standard for the assessment of building energy performance. Applied Energy 2019; 254. doi:10.1016/j.apenergy.2019.113553.

[382] Government of British Columbia. BC Energy Step Code: A Best Practices Guide for local governments. Victoria: 2017.

[383] City of Vancouver. Energy Modelling Guidelines Version 2.0. Vancouver: 2018.

[384] Tokarik MS, Richman RC. Life cycle cost optimization of passive energy efficiency improvements in a Toronto house. Energy and Buildings 2016; 118:160–9. doi:10.1016/j.enbuild.2016.02.015.

[385] Katsaprakakis D Al, Georgila K, Zidianakis G, Michopoulos A, Psarras N, Christakis DG, et al. Energy upgrading of buildings. A holistic approach for the Natural History Museum of Crete, Greece. Renewable Energy 2017; 114:1306–32. doi:10.1016/j.renene.2017.08.021.

[386] RSMeans. RSMeans construction cost data. Kingston, MA: RS Means Company; 2019.

[387] Li H, Wang S, Cheung H. Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions. Applied Energy 2018;228:1280–91. doi:10.1016/j.apenergy.2018.07.023.

[388] Yildiz Y, Arsan ZD. Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates. Energy 2011; 36:4287–96. doi:10.1016/j.energy.2011.04.013.

[389] Chen X, Yang H, Zhang W. A comprehensive sensitivity study of major passive design parameters for the public rental housing development in Hong Kong. Energy 2015; 93:1804–18. doi:10.1016/j.energy.2015.10.061.

[390] Jin Q, Overend M. Sensitivity of façade performance on early-stage design variables. Energy and Buildings 2014; 77:457–66. doi:10.1016/j.enbuild.2014.03.038.

[391] Schleich J, Gruber E. Beyond case studies: Barriers to energy efficiency in commerce and the services sector. Energy Economics 2008; 30:449–64. doi:10.1016/j.eneco.2006.08.004.

[392] Mills E, Kromer S, Weiss G, Mathew PA. From volatility to value: Analysing and managing financial and performance risk in energy savings projects. Energy Policy 2006; 34:188–99. doi:10.1016/j.enpol.2004.08.042.

[393] ASHRAE. 2013 ASHRAE Handbook - Fundamentals (SI Edition). American Society of Heating Refrigerating and Air-Conditioning Engineers Inc.; 2013.

[394] Kwok SSK, Yuen RKK, Lee EWM. An intelligent approach to assessing the effect of building occupancy on building cooling load prediction. Building and Environment 2011; 46:1681–90. doi:10.1016/j.buildenv.2011.02.008.

[395] ASHRAE. American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE handbook: energy estimating and modeling methods 2005.

[396] NREL. BEopt Building Energy Optimization Tool 2020. https://beopt.nrel.gov/home (accessed November 27, 2020).

[397] Rhodes JD, Gorman WH, Upshaw CR, Webber ME. Using BEopt (EnergyPlus) with energy audits and surveys to predict actual residential energy usage. Energy and Buildings 2015; 86:808–16. doi:10.1016/j.enbuild.2014.10.076.

[398] Alemi P, Loge F. Energy efficiency measures in affordable zero net energy housing: A case study of the UC Davis 2015 Solar Decathlon home. Renewable Energy 2017; 101:1242–55. doi:10.1016/j.renene.2016.10.016.

[399] Murphy R, Boyd K, Jaccard M. Evaluation of Actions and Policies to Reduce Urban GHG Emissions Using Multiple Criteria: A Contribution Towards Energy Efficiency in British Columbia's Built Environment. 2016.

[400] Christensen C, Horowitz S, Givler T, Courtney A, Barker G. BEopt: software for identifying optimal building designs on the path to net zero energy ISES. Solar World Congress, Orlando, FL: 2005.

[401] Heiselberg P, Brohus H, Hesselholt A, Rasmussen H, Seinre E, Thomas S. Application of sensitivity analysis in design of sustainable buildings. Renewable Energy 2009;3 4:2030–6. doi:10.1016/j.renene.2009.02.016.

[402] Stephan A, Stephan L. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. Applied Energy 2020; 280:115932. doi:10.1016/j.apenergy.2020.115932.

[403] Hamby DM. A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment 1994; 32:135–54. doi:10.1007/BF00547132.

[404] Berardi U, Soudian S. Benefits of latent thermal energy storage in the retrofit of Canadian high-rise residential buildings. Building Simulation 2018 ;11:709–23. doi:10.1007/s12273-018-0436-x.

[405] Asaee SR, Ugursal VI, Beausoleil-Morrison I. Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings. Energy Policy 2019; 126:118–30. doi:10.1016/j.enpol.2018.10.055.

[406] Kheiri F. A review on optimization methods applied in energy-efficient building geometry and envelope design. Renewable and Sustainable Energy Reviews 2018; 92:897–920. doi:10.1016/j.rser.2018.04.080.

[407] Golbazi M, Aktas CB. Analysis on the effects of exterior openings on residential building energy consumption in Northeast U.S. climate conditions. 4th Residential Building Design & Construction Conference, 2018.

[408] Copiello S, Gabrielli L, Bonifaci P. Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate. Energy 2017; 137:104–17. doi:10.1016/j.energy.2017.06.159.

[409] British Columbia's Carbon Tax 2018..

[410] World Bank. State and trends of carbon pricing 2014. 2014.

[411] Govt. of British Columbia. British Columbia's Carbon Tax_Delayed Carbon Tax

[412] BC Housing Research Centre. 2018 BC Residential Building Statistics & Trends Report. 2019.

[413] FortisBC. New Home Program – special rebates for a limited time 2020. https://www.fortisbc.com/rebates/home/new-home-construction-rebates (accessed November 13, 2020).

[414] StatsCanada. Data tables, 2016 Census 2016. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/dt-td/Rp-eng.cfm?.

[415] Chen X, Yang H. A multi-stage optimization of passively designed high-rise residential buildings in multiple building operation scenarios. Applied Energy 2017; 206:541–57. doi:10.1016/j.apenergy.2017.08.204.

[416] CMHC-SCHL. Universal Design for New Housing Units 2019. https://www.cmhc-schl.gc.ca/en/developing-and-renovating/accessible-adaptable-housing/universal-design-in-new-housing.

[417] Sartori I, Napolitano A, Voss K. Net zero energy buildings: A consistent definition framework. Energy and Buildings 2012; 48:220–32. doi:10.1016/j.enbuild.2012.01.032.

[418] GasExperts.ca 2020. https://www.gasexperts.ca/page/1/?s=SRE&post_type=producthttps://www.gasexperts.ca/product/lifebreath-max-series-model-267-max-hrv/https://www.gasexperts.ca/page/1/?s=SRE&post_type=product.

[419] Wright GS, Klingenberg K, Pettit B. Building america report—1405 Climate-Specific Passive Building Standards. Springfield, VA: 2015.

[420] Fletcher T. B.C. carbon tax now costs more than natural gas it is charged 2018. https://www.vicnews.com/business/b-c-carbon-tax-now-costs-more-than-natural-gas-it-is-charged-on/ (accessed November 27, 2020).

[421] FortisBC. Accounts & billing 2020. doi:10.1016/j.tmaid.2020.101613.

[422] Statistics Canada. Data tables, 2016 Census. Structural Type of Dwelling (10) and Household Size (8) for Occupied Private Dwellings of Canada, Provinces and Territories, Census Divisions and Census Subdivisions, 2016 Census - 100% Data. 2016.

[423] BC Housing Research Centre. December 2020-British Columbia's Monthly New Homes Registry Report. 2020.

[424] Kneifel JD, Lippiatt BC. Cost-effectiveness, Carbon Emissions, and Carbon Tax Implications of Energy Efficiency Measures in New Commercial Buildings. 8th Workshop pf CIB W108 Climate Change and the Built Environment, Milan (Italy): 2009, p. 48–52.

[425] Fischer C, Newell RG. Environmental and technology policies for climate mitigation. Journal of Environmental Economics and Management 2008; 55:142–62. doi:10.1016/j.jeem.2007.11.001.

[426] Lin B, Li X. The effect of carbon tax on per capita CO2 emissions. Energy Policy 2011; 39:5137–46. doi:10.1016/j.enpol.2011.05.050.

[427] Chen W, Jin R, Sudjiant A. Analytical variance-based global sensitivity analysis in simulation-based design under uncertainty 2005.

[428] Lamboni M. Multivariate sensitivity analysis: Minimum variance unbiased estimators of the first-order and total-effect covariance matrices. Reliability Engineering and System Safety 2019; 187:67–92. doi:10.1016/J.RESS.2018.06.004.

[429] Riedy C, Diesendorf M. Financial subsidies to the Australian fossil fuel industry. Energy Policy 2003; 31:125–37. doi:10.1016/S0301-4215(02)00017-4.

[430] Salter J, Lu Y, Kim JC, Kellett R, Girling C, Inomata F, et al. Iterative 'what-if'neighborhood simulation: energy and emissions impacts. Buildings and Cities 2020; 1:293–307. doi:10.5334/bc.51.

[431] Yannick GZS, Hongzhong Z, Thierry B. Technical Efficiency Assessment Using Data Envelopment Analysis: An Application to the Banking Sector of Côte D'Ivoire. Procedia - Social and Behavioral Sciences 2016; 235:198–207. doi:10.1016/j.sbspro.2016.11.015.

[432] Charnes A, Cooper WW, Rhodes E. Measuring the efficiency of decision making units. European Journal of Operational Research 1978; 2:429–44.

[433] Contreras I. Optimizing the rank position of the DMU as secondary goal in DEA cross-evaluation. Applied Mathematical Modelling 2012; 36:2642–8. doi:10.1016/j.apm.2011.09.046.

[434] Mardani A, Streimikiene D, Balezentis T, Saman MZM, Nor KM, Khoshnava SM. Data envelopment analysis in energy and environmental economics: an overview of the state-of-the-art and recent development trends. Energies 2018; 11:2002. doi:10.3390/en11082002.

[435] Yu MM, Chen LH, Hsiao B. A performance-based subsidy allocation of ferry transportation: A data envelopment approach. Transport Policy 2018; 68:13–9. doi:10.1016/j.tranpol.2018.04.004.

[436] Xie Q, Dai Q, Mita S, Long Q, Li Y. Investigate the relationship between the super-efficiency and fixed input in the presence of infeasibility. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 2013, p. 2026–32. doi:10.1109/ITSC.2013.6728527.

[437] Ang S, Chen M, Yang F. Group cross-efficiency evaluation in data envelopment analysis: An application to Taiwan hotels. Computers and Industrial Engineering 2018; 125:190–9. doi:10.1016/j.cie.2018.08.028.

[438] Vankova I. Technical Efficiency of Retirement Homes Aggregated in Particular Districts of the Czech Republic. Proceedings of the 13th international scientific conference public economics and administration, 2019.

[439] Bandara RMPS, Attalage RA. Optimization of Building Performance in terms of Envelope Elements through combined Energy Modelling and Generic Optimization. Applied Mechanics and Materials 2014;592.

[440] Wang E, Shen Z, Alp N, Barry N. Benchmarking energy performance of residential buildings using two-stage multifactor data envelopment analysis with degree-day based simple-normalization approach. Energy Conversion and Management 2015;106:530–42. doi:10.1016/j.enconman.2015.09.072.

[441] Grösche P. Measuring residential energy efficiency improvements with DEA. Journal of Productivity Analysis 2009;31:87–94. doi:10.1007/s11123-008-0121-7.

[442] Sokol J, Cerezo Davila C, Reinhart CF. Validation of a Bayesian-based method for defining residential archetypes in urban building energy models. Energy and Buildings 2017;134:11–24. doi:10.1016/j.enbuild.2016.10.050.

[443] United States Census Bureau. American Housing Survey (AHS) 2019. https://www.census.gov/programs-surveys/ahs/data.html.

[444] U.S. Energy Information Administration. U.S. Energy Information Administration, Residential Energy Consumption Survey (RECS) Data 2015.

[445] European Union. Typology Approach for Building Stock Energy Assessment (TABULA) n.d.

[446] Krarti M. Chapter 9-Analysis of Large-Scale Energy Efficiency Programs. Optimal Design and Retrofit of Energy Efficient Buildings, Communities, and Urban Centers, Butterworth-Heinemann; 2018, p. 547–610. doi:10.1016/C2016-0-02074-0.

[447] Kavgic M, Mavrogianni A, Mumovic D, Summerfield A, Stevanovic Z, Djurovic-Petrovic M. A review of bottom-up building stock models for energy consumption in the residential sector. Building and Environment 2010; 45:1683–97. doi:10.1016/j.buildenv.2010.01.021.

[448] Snäkin JP. An engineering model for heating energy and emission assessment. The case of North Karelia, Finland. Applied Energy 2000; 67:353–81. doi:10.1016/S0306-2619(00)00035-0.

[449] Huang YJ, Brodrick J. No TitleA bottom-up engineering estimate of the aggregate heating and cooling loads of the entire US building stock. 2000 ACEEE Summer Study on Energy Efficiency inBuildings, Pacific Grove, CA, August 20-25, 2000, 2000.

[450] Peng H, He M, Li M, Huang Y, Wen L. Investigation on spatial distributions and occupant schedules of typical residential districts in South China's Pearl River Delta. Energy and Buildings 2020; 209. doi:10.1016/j.enbuild.2019.109710.

[451] Penna P, Prada A, Cappelletti F, Gasparella A, Penna P, Prada A, et al. Multi-objective optimization for existing buildings retrofitting under government subsidization. Science & Technology for the Built Environment 2015;21:847–61. doi:10.1080/23744731.2015.1028867.

[452] Zhang MM, Zhou DQ, Zhou P, Chen HT. Optimal design of subsidy to stimulate renewable energy investments: The case of China. Renewable and Sustainable Energy Reviews 2017;71:873–83. doi:10.1016/J.RSER.2016.12.115.

[453] Sueyoshi T, Goto M. Environmental assessment on energy and sustainability by data envelopment analysis. John Wiley & Sons.; 2018.

[454] Farrell M. The measurement of productive efficiency. Journal of Royal Statistics Society 1957;120:253–81.

[455] Amores AF, Contreras I. New approach for the assignment of new European agricultural subsidies using scores from data envelopment analysis: Application to olive-growing farms in Andalusia (Spain). European Journal of Operational Research 2009; 193:718–29. doi:10.1016/J.EJOR.2007.06.059.

[456] Wu D, Qi H. Evaluating the economic and ecological impact for small and medium airport subsidies in China. Journal of Cleaner Production 2021; 281. doi:10.1016/j.jclepro.2020.124811.

[457] Ramanathan R. An introduction to data envelopment analysis: a tool for performance measurement 2003.

[458] Rana A, Dyck R, Hu G, Hewage K, Rodriguez MJ, Alam MS, et al. A process-based LCA for selection of low-impact DBPs control strategy for indoor swimming pool operation. Journal of Cleaner Production 2020;270. doi:10.1016/j.jclepro.2020.122372.

[459] Zwiener C, Richardson SD, De Marini DM, Grummt T, Glauner T, Frimmel FH. Drowning In Disinfection Byproducts? Assesing Swimming Pool Water. Journal of Environmental Science & Technology 2007; 41:363–72.

[460] WHO. Guidelines for Safe Recreational Water Environments, Swimming Pools, Spas and Similar Recreational Water Environments 2006.

[461] Statistics Canada. Government of Canada Statistics-Infrastructure Canada 2016. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3410006701.

[462] Kanan A. Occurrence and formation of disinfection by-products in indoor swimming pools water. Clemson University, 2010.

[463] Olsen K. Clear waters and a green gas: a history of chlorine as a swimming pool sanitizer in the United States. Bull Hist Chem 2007; 32:129–40.

[464] Hsu HT, Chen MJ, Lin CH, Chou WS, Chen JH. Chloroform in indoor swimming-pool air: Monitoring and modeling coupled with the effects of environmental conditions and occupant activities. Water Research 2009; 43:3693–704. doi:10.1016/j.watres.2009.05.032.

[465] Kim H, Shim J, Lee S. Formation of disinfection by-products in chlorinated swimming pool water. Chemosphere 2002; 46:123–30. doi:10.1016/S0045-6535(00)00581-6.

[466] Manasfi T, Coulomb B, Boudenne JL. Occurrence, origin, and toxicity of disinfection byproducts in chlorinated swimming pools: An overview. International Journal of Hygiene and Environmental Health 2017; 220:591–603. doi:10.1016/j.ijheh.2017.01.005.

[467] Aprea M-C, Banchi B, Lunghini L, Pagliantini M, Peruzzi A, Sciarra G. Disinfection of swimming pools with chlorine and derivatives: formation of organochlorinated and organobrominated compounds and exposure of pool personnel and swimmers. Natural Science 2010; 02:68–78. doi:10.4236/ns.2010.22011.

[468] Rahman MB, Driscoll T, Cowie C, Armstrong BK. Disinfection by-products in drinking water and colorectal cancer: a meta-analysis. International Journal of Epidemiology 2010; 39:733–45. doi:10.1093/ije/dyp371.

[469] Villanueva CM, Font-Ribera L. Health impact of disinfection by-products in swimming pools. Annali Dell'Istituto Superiore Di Sanità 2012; 48:387–96. doi:10.4415/ANN_12_04_06.

[470] Dyck R, Sadiq R, Rodriguez MJ, Simard S, Tardif R. Trihalomethane exposures in indoor swimming pools: A level III fugacity model. Water Research 2011; 45:5084–98. doi:10.1016/j.watres.2011.07.005.

[471] Bernard A, Nickmilder M, Voisin C, Sardella A. Impact of Chlorinated Swimming Pool Attendance on the Respiratory Health of Adolescents. PEDIATRICS 2009; 124:1110–8. doi:10.1542/peds.2009-0032.

[472] Weisel CP, Richardson SD, Nemery B, Aggazzotti G, Baraldi E, Blatchley ER, et al. Childhood Asthma and Environmental Exposures at Swimming Pools: State of the Science and Research Recommendations. Environmental Health Perspectives 2009; 117:500–7. doi:10.1289/ehp.11513.

[473] Voisin C, Sardella A, Bernard A. Risks of new-onset allergic sensitization and airway inflammation after early age swimming in chlorinated pools. International Journal of Hygiene and Environmental Health 2014; 217:38–45. doi:10.1016/j.ijheh.2013.03.004.

[474] Villanueva CM, Cantor KP, Grimalt JO, Malats N, Silverman D, Tardon A, et al. Bladder cancer and exposure to water disinfection by-products through ingestion, bathing,

showering, and swimming in pools. American Journal of Epidemiology 2007; 165:148–56. doi:10.1093/aje/kwj364.

[475] Rashid AAF, Yusoff S. A review of life cycle assessment method for building industry. Renewable and Sustainable Energy Reviews 2015; 45:244–8. doi:10.1016/j.rser.2015.01.043.

[476] Hery M, Hecht G, Gerber JM, Gender JC, Hubert G, Rebuffaud J. Exposure to chloramines in the atmosphere of indoor swimming pools. The Annals of Occupational Hygiene 1995; 1:427–39. doi:10.1093/annhyg/39.4.427.

[477] Daiber EJ, DeMarini DM, Ravuri SA, Liberatore HK, Cuthbertson AA, Thompson-Klemish A, et al. Progressive Increase in Disinfection Byproducts and Mutagenicity from Source to Tap to Swimming Pool and Spa Water: Impact of Human Inputs. Environmental Science & Technology 2016; 50:6652–62. doi:10.1021/acs.est.6b00808.

[478] LaKind JS, Richardson SD, Blount BC. The Good, the Bad, and the Volatile: Can We Have Both Healthy Pools and Healthy People? Environmental Science & Technology 2010; 44:3205–10. doi:10.1021/es903241k.

[479] Hansen KMS, Willach S, Antoniou MG, Mosbæk H, Albrechtsen H-J, Andersen HR. Effect of pH on the formation of disinfection byproducts in swimming pool water – Is less THM better? Water Research 2012; 46:6399–409. doi:10.1016/j.watres.2012.09.008.

[480] Simard S, Tardif R, Rodriguez MJ. Variability of chlorination by-product occurrence in water of indoor and outdoor swimming pools. Water Research 2013; 47:1763–72. doi:10.1016/j.watres.2012.12.024.

[481] Kanan A, Karanfil T. Formation of disinfection by-products in indoor swimming pool water: The contribution from filling water natural organic matter and swimmer body fluids. Water Research 2011; 45:926–32. doi:10.1016/j.watres.2010.09.031.

[482] Lee J, Ha K-T, Zoh K-D. Characteristics of trihalomethane (THM) production and associated health risk assessment in swimming pool waters treated with different disinfection methods. Science of The Total Environment 2009; 407:1990–7. doi:10.1016/j.scitotenv.2008.11.021.

[483] McMaster ME. Heated indoor swimming pools, infants, and the pathogenesis of adolescent idiopathic scoliosis: a neurogenic hypothesis. Environmental Health: A Global Access Science Source 2011; 10:86. doi:10.1186/1476-069X-10-86.

[484] Richardson SD, DeMarini DM, Kogevinas M, Fernandez P, Marco E, Lourencetti C, et al. What's in the Pool? A Comprehensive Identification of Disinfection By-products and Assessment of Mutagenicity of Chlorinated and Brominated Swimming Pool Water. Environmental Health Perspectives 2010; 118:1523–30. doi:10.1289/ehp.1001965.

[485] Kristensen GH, Klausen MM, Hansen VA, Lauritsen FR. On-line monitoring of the dynamics of trihalomethane concentrations in a warm public swimming pool using an unsupervised membrane inlet mass spectrometry system with off-site real-time surveillance. Rapid Communications in Mass Spectrometry 2010; 24:30–4. doi:10.1002/rcm.4360.

[486] Chu H, Nieuwenhuijsen MJ. Distribution and determinants of trihalomethane concentrations in indoor swimming pools. Occupational and Environmental Medicine 2002;59:243–7.

[487] Jacobs JH, Spaan S, van Rooy GBGJ, Meliefste C, Zaat VAC, Rooyackers JM, et al. Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. European Respiratory Journal 2007; 29:690–8. doi:10.1183/09031936.00024706.

[488] Bessonneau V, Derbez M, Clément M, Thomas O. Determinants of chlorination by-products in indoor swimming pools. International Journal of Hygiene and Environmental Health 2011; 215:76–85. doi:10.1016/j.ijheh.2011.07.009.

[489] Castor ML, Beach MJ. Reducing Illness Transmission from Disinfected Recreational Water Venues. The Pediatric Infectious Disease Journal 2004; 23:866–70. doi:10.1097/01.inf.0000138081.84891.30.

[490] US EPA. Alternative disinfectants and oxidants guidance manual (Vol. 99, No. 14) 1999.

[491] Skibinski B, Uhlig S, Müller P, Slavik I, Uhl W. Impact of Different Combinations of Water Treatment Processes on the Concentration of Disinfection Byproducts and Their

Precursors in Swimming Pool Water. Environmental Science and Technology 2019. doi:10.1021/acs.est.9b00491.

[492] Tardif R, Catto C, Haddad S, Rodriguez M. Assessment of worker exposure to disinfection byproducts at indoor swimming pools in Québec. 2016.

[493] Ilyas H, Masih I, van der Hoek J. Disinfection Methods for Swimming Pool Water: Byproduct Formation and Control. Water 2018; 10:797. doi:10.3390/w10060797.

[494] Gerrity D, Mayer B, Ryu H, Crittenden J, Abbaszadegan M. A comparison of pilot-scale photocatalysis and enhanced coagulation for disinfection byproduct mitigation. Water Research 2009; 43:1597–610. doi:10.1016/j.watres.2009.01.010.

[495] Yang L, Chen X, She Q, Cao G, Liu Y, Chang VW-C, et al. Regulation, formation, exposure, and treatment of disinfection by-products (DBPs) in swimming pool waters: A critical review. Environment International 2018; 121:1039–57. doi:10.1016/j.envint.2018.10.024.

[496] Baxter BRC. Designing for IAQ In Natatoriums 2012.

[497] Rugani B, Panasiuk D, Benetto E. An input–output based framework to evaluate human labour in life cycle assessment. The International Journal of Life Cycle Assessment 2012; 17:795–812. doi:10.1007/s11367-012-0403-1.

[498] Souto-Martinez A, Liel AB, SrubarIII W V. Embodied Carbon in Buildings-Measurement, Management, and Mitigation. Springer International Publishing; 2018. doi: 10.1007/978-3-319-72796-7.

[499] Alvarez S, Rubio A. Compound method based on financial accounts versus process-based analysis in product carbon footprint: A comparison using wood pallets. Ecological Indicators 2015; 49:88–94. doi:10.1016/j.ecolind.2014.10.005.

[500] Yang Y, Heijungs R, Brandão M. Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. Journal of Cleaner Production 2017; 150:237–42. doi:10.1016/j.jclepro.2017.03.006.

[501] ISO 14040:2006(en). Environmental management — Life cycle assessment — Principles and framework. ISO 14040:2006 2006.

[502] Klüppel H-J. ISO 14041: Environmental management — life cycle assessment — goal and scope definition — inventory analysis. The International Journal of Life Cycle Assessment 1998; 3:301–301. doi:10.1007/BF02979337.

[503] Lenzen M. Errors in Conventional and Input-Output—based Life—Cycle Inventories. Journal of Industrial Ecology 2000; 4:127–48. doi:10.1162/10881980052541981.

[504] Majeau-Bettez G, Strømman AH, Hertwich EG. Evaluation of Process- and Input–Output-based Life Cycle Inventory Data with Regard to Truncation and Aggregation Issues. Environmental Science & Technology 2011; 45:10170–7. doi:10.1021/es201308x.

[505] Isaac PRD, Hayes CR, Akers RK. Optimisation of water and energy use at the Wales National Pool. Water and Environment Journal 2010; 24:39–48. doi:10.1111/j.1747-6593.2008.00150.x.

[506] Duverge JJ, Rajagopalan P, Fuller R. Defining aquatic centres for energy and water benchmarking purposes. Sustainable Cities and Society 2017; 31:51–61. doi:10.1016/J.SCS.2017.02.008.

[507] Marinopoulos IS, Katsifarakis KL. Optimization of Energy and Water Management of Swimming Pools. A Case Study in Thessaloniki, Greece. Procedia Environmental Sciences 2017; 38:773–80. doi:10.1016/j.proenv.2017.03.161.

[508] Kampel W, Aas B, Bruland A. Energy-use in Norwegian swimming halls. Energy and Buildings 2013;59:181–6. doi:10.1016/j.enbuild.2012.11.011.

[509] Trianti-Stourna E, Spyropoulou K, Theofylaktos C, Droutsa K, Balaras CA, Santamouris M, et al. Energy conservation strategies for sports centers: Part B. Swimming pools. Energy and Buildings 1998;27:123–35. doi:10.1016/S0378-7788(97)00041-8.

[510] Lewis L, Chew J, Woodley I, Colbourne J, Pond K. Modifications for water management guidance based on an assessment of swimming pool water consumption of an operational facility in the UK. Water Science and Technology: Water Supply 2015; 15:965–73. doi:10.2166/ws.2015.049.

[511] Liu W, Cheung L-M, Yang X, Shang C. THM, HAA and CNCl formation from UV irradiation and chlor(am)ination of selected organic waters. Water Research 2006; 40:2033–43. doi:10.1016/j.watres.2006.03.019.

[512] Forrest N, Williams E. Life Cycle Environmental Implications of Residential Swimming Pools. Environmental Science {&} Technology 2010; 44:5601–7. doi:10.1021/es100422s.

[513] ISO 14044. Environmental Management-Life Cycle Assessment-Requirements and guidelines 2006.

[514] Van Ooteghem K, Xu L. The life-cycle assessment of a single-storey retail building in Canada. Building and Environment 2012; 49:212–26. doi:10.1016/j.buildenv.2011.09.028.

[515] Kofoworola OF, Gheewala SH. Life cycle energy assessment of a typical office building in Thailand. Energy and Buildings 2009; 41:1076–83. doi:10.1016/j.enbuild.2009.06.002.

[516] ANSES. Évaluation des risques sanitaires liés aux piscines Partie I: piscines réglementées. Avis de l'ANSES. Rapport d'expertise collective. 2012; 978-2-11-129542-1.

[517] DIN. Treatment of Water of Swimming Pools and Baths – Part 1: General Requirements (English translation of DIN 2012. 19643-1. Erlin, Germany: 2012.

[518] MHURD. Water Quality Standards for Swimming Pool. People's Republic of China. CJ/T-244-2016 2016.

[519] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 2016; 21:1218–30. doi:10.1007/s11367-016-1087-8.

[520] Corominas L, Foley J, Guest JS, Hospido A, Larsen HF, Morera S, et al. Life cycle assessment applied to wastewater treatment: State of the art. Water Research 2013; 47:5480–92. doi:10.1016/j.watres.2013.06.049.

[521] NRCan. Enerpool 3.0 | Natural Resources Canada 2013. https://www.nrcan.gc.ca/energy/software-tools/7437 (accessed February 20, 2019).

[522] Spellman FR. Handbook of water and wastewater treatment plant operations. CRC press.; 2013.

[523] Ghimire SR, Johnston JM, Ingwersen WW, Sojka S. Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system. Journal of Cleaner Production 2017; 151:74–86. doi:10.1016/j.jclepro.2017.02.025.

[524] Prism Engineering. Energy Calculators 2019. https://www.prismengineering.com/resources/calculators.

[525] Engieering Toolbox. Power Gained by Fluid from Pump or Fan. 2004. https://www.engineeringtoolbox.com/pump-fan-power-d_632.html.

[526] Hordeski MF. New technologies for energy efficiency. Fairmont Press; 2002.

[527] Chang Y, Reardon DJ, Kwan P, Boyd G, Brant J, Rakness KL, et al. Evaluation of dynamic energy consumption of advanced water and wastewater treatment technologies. Denver: 2008.

[528] Pirnie M. Optimizing the energy efficiency of ultraviolet disinfection through on-site validation and control equipment maintenance. New York State: 2005.

[529] Water Environment Federation. Energy conservation in water and wastewater treatment facilities. WEF Manual. Alexandria, Virginia: Water Environment Federation (WEF); 2009.

[530] Gallion T, Harrison T, Hulverson R, Hristovski K. Estimating Water, Energy, and Carbon Footprints of Residential Swimming Pools. Water Reclamation and Sustainability, Elsevier; 2014, p. 343–59. doi:10.1016/B978-0-12-411645-0.00014-6.

[531] Rajagopalan P. Energy performance of aquatic facilities in Victoria, Australia. Facilities 2014;32:565–80. doi:10.1108/F-02-2013-0015.

[532] Shah MM. Improved method for calculating evaporation from indoor water pools. Energy and Buildings 2012;49:306–9. doi:10.1016/j.enbuild.2012.02.026.

[533] MJMA and Acton Ostry Architects. UBC Aquatic Centre, Mechanical Schedule 2014.

[534] Shah MM. New Correlation for Prediction of Evaporation from Occupied Swimming Pools. ASHRAE Transactions 2013;119.

[535] AWWA. Water Audits and Loss Control Programs: M36. American Water Works Association; 2008.

[536] Mian HR, Hu G, Hewage K, Rodriguez MJ, Sadiq R. Prioritization of unregulated disinfection by-products in drinking water distribution systems for human health risk mitigation: A critical review. Water Research 2018; 147:112–31. doi:10.1016/j.watres.2018.09.054.

[537] PRé Consultants. Software to measure and improve the impact of your product life cycle | PRé Sustainability. (2016). 2016. https://www.pre-sustainability.com/simapro (accessed September 14, 2016).

[538] Ciroth A, Finkbeier M, Hildenbrand J, Klöpffer W, Mazijn B, Prakash S, et al. Towards a live cycle sustainability assessment: making informed choices on products. 2011.

[539] PRé Sustainability. SimaPro Database Manual: Methods Library 2016.

[540] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment 2017; 22:138–47. doi:10.1007/s11367-016-1246-y.

[541] Ochsendorf J, Keith Norford L, Brown D, Durschlag H, Hsu SL, Love A, et al. Methods, impacts, and opportunities in the concrete building life cycle 2011.

[542] ASTM International. ASTM Standards E1991-05-Standard guide for environmental life cycle assessment (LCA) of building materials/products 2005:1–9.

[543] ISO 14040. Environmental Management-Life Cycle Assessment-Principles and framework. Geneva: International Organization for Standardization; 2006.

[544] Myllyviita T, Holma A, Antikainen R, Lähtinen K, Leskinen P. Assessing environmental impacts of biomass production chains - Application of life cycle assessment (LCA) and multi-criteria decision analysis (MCDA). Journal of Cleaner Production 2012; 29–30:238–45. doi:10.1016/j.jclepro.2012.01.019.

[545] Prado V, Wender BA, Seager TP. Interpretation of comparative LCAs: external normalization and a method of mutual differences. The International Journal of Life Cycle Assessment 2017; 22:2018–29. doi:10.1007/s11367-017-1281-3.

[546] Zanghelini GM, Cherubini E, Soares SR. How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation. Journal of Cleaner Production 2018; 172:609–22. doi:10.1016/j.jclepro.2017.10.230.

[547] Bauer C, Heck T, Hirschberg S, Dones R. Environmental assessment of current and future Swiss electricity supply options 2008.

[548] Zagonari F. Four sustainability paradigms for environmental management: A methodological analysis and an empirical study based on 30 Italian industries. Sustainability 2016; 8:504.

[549] Kumar V, Hewage K, Haider H, Sadiq R. Sustainability evaluation framework for building cooling systems: a comparative study of snow storage and conventional chiller systems. Clean Technologies and Environmental Policy 2017; 19:137–55. doi:10.1007/s10098-016-1198-8.

[550] Tang Y, You F. Life cycle environmental and economic analysis of pulverized coal oxy-fuel combustion combining with calcium looping process or chemical looping air separation. Journal of Cleaner Production 2018; 181:271–92. doi:10.1016/j.jclepro.2018.01.265.

[551] Sohn JL, Kalbar PP, Birkved M. Life cycle based dynamic assessment coupled with multiple criteria decision analysis: A case study of determining an optimal building insulation level. Journal of Cleaner Production 2017;162:449–57. doi:10.1016/j.jclepro.2017.06.058.

[552] Kalbar PP, Birkved M, Nygaard SE, Hauschild M. Weighting and Aggregation in Life Cycle Assessment: Do Present Aggregated Single Scores Provide Correct Decision Support? Journal of Industrial Ecology 2016; 21:1591–600. doi:10.1111/jiec.12520.

[553] Ramsey M. New UBC Aquatic Centre – Facts and Figures 2017. https://news.ubc.ca/2017/01/17/new-ubc-aquatic-centre-facts-and-figures/ (accessed February 20, 2020).

[554] MJMA and Acton Ostry Architects. UBC Aquatic Centre Mechanical Schedule, Drawing No. E270 2014.

[555] Saleem S, Dyck R, Hu G, Hewage K, Rodriguez M, Sadiq R. Investigating the effects of design and management factors on DBPs levels in indoor aquatic centres. Science of The Total Environment 2019; 651:775–86. doi:10.1016/j.scitotenv.2018.09.172.

[556] Duverge JJ, Rajagopalan P, Fuller R, Woo J. Energy and water benchmarks for aquatic centres in Victoria, Australia. Energy and Buildings 2018; 177:246–56. doi:10.1016/j.enbuild.2018.07.043.

[557] RMS. Drinking Water Quality. Risk Management Services, UBC Vancouver 2017. http://rms.ubc.ca/environment/drinkingwater/.

[558] Lau M. Making Waves With Sustainability at UBC Aquatic Centre | New UBC Aquatic Centre. UBC Vancouver 2017. http://recreation-aquatics.sites.olt.ubc.ca/2017/01/24/sustainability-at-ubc-aquatic-centre/ (accessed March 20, 2018).

[559] Street R. UBC Aquatic Centre Facilities Manager, Maintenance, Safety & Sustainability 2017.

[560] Ministry of Health. B.C. Guidelines for swimming pool operators 2014.

[561] Akella AK, Saini RP, Sharma MP, Klein K, Gaines L, Oduor J a., et al. Geothermal Public Health Assessment. FIG Congress 2010 2013; 34:1–17. doi:10.1016/j.renene.2008.05.002.

[562] Bardhan R, Debnath R, Jana A, Norford LK. Investigating the association of healthcare-seeking behavior with the freshness of indoor spaces in low-income tenement housing in Mumbai. Habitat International 2018; 71:156–68. doi:10.1016/j.habitatint.2017.12.007.

[563] Csiszar SA, Meyer DE, Dionisio KL, Egeghy P, Isaacs KK, Price PS, et al. Conceptual Framework To Extend Life Cycle Assessment Using Near-Field Human Exposure

Modeling and High-Throughput Tools for Chemicals. Environmental Science & Technology 2016; 50:11922–34. doi:10.1021/acs.est.6b02277.

[564] IEA. OECD electricity production by source 1974-2016 2017.

[565] Bush E, Lemmen DS. Canada's Changing Climate Report (CCCR). Ottawa: 2019.

[566] Religious buildings initiative. Manitoba Hydro 2018. https://www.hydro.mb.ca/your_business/benchmarking/religious_buildings/index.shtml (accessed August 23, 2018).

[567] Energy-Efficient Housing Program. Genworth Canada 2018. https://www.genworth.ca/en/products/energy-efficient-housing.aspx (accessed August 23, 2018).

[568] Central or ductless heat pump loans. FortisBC_Electricity 2018. https://www.fortisbc.com/Rebates/RebatesOffers/AirSourceHeatPumpLoan/Pages/default.aspx (accessed August 23, 2018).

[569] Residential Earth Power Loan. Manitoba Hydro 2018. https://www.hydro.mb.ca/your_home/power_smart/earth_power_loan/qualifying_upgrades.shtml (accessed August 23, 2018).

[570] TakeCHARGE. Newfoundland Power and Newfoundland and Labrador Hydro 2018. https://takechargenl.ca/residential/rebate-programs/thermostat-rebate/ (accessed August 27, 2018).

[571] Directory of Energy Efficiency and Alternative Energy Programs in Canada. NRC 2017. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/policy_e/ (accessed August 23, 2018).

[572] SaskPower 2018. https://www.saskpower.com/ (accessed August 27, 2018).

[573] Murray B, Rivers N. British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy. Energy Policy 2015; 86:674–83. doi:10.1016/j.enpol.2015.08.011.

[574] Timmons D, Konstantinidis C, Shapiro AM, Wilson A. Decarbonizing residential building energy: A cost-effective approach. Energy Policy 2016; 92:382–92. doi:10.1016/j.enpol.2016.02.030.

[575] Kiani A. Coupling effects of demand-side improvements ensemble on energy performance to monetary implications for UAE economy. Journal of Cleaner Production 2017; 167:44–54. doi:10.1016/j.jclepro.2017.08.133.

[576] Matisoff DC, Johnson EP. The comparative effectiveness of residential solar incentives. Energy Policy 2017; 108:44–54. doi:10.1016/j.enpol.2017.05.032.

[577] Fan Y, Xia X. Energy-efficiency building retrofit planning for green building compliance. Building and Environment 2018;136:312–21. doi:10.1016/j.buildenv.2018.03.044.

[578] Voulis N, van Etten MJJ, Chappin ÉJL, Warnier M, Brazier FMT. Rethinking European energy taxation to incentivise consumer demand response participation. Energy Policy 2019; 124:156–68. doi:10.1016/j.enpol.2018.09.018.

[579] Logue JM, Turner WJ, Walker IS, Singer BC. A simplified model for estimating population-scale energy impacts of building envelope air tightening and mechanical ventilation retrofits. Journal of Building Performance Simulation 2016; 9:1–6. doi:10.1080/19401493.2014.993710.

[580] Parekh A, Charron R, Poirier S, Roux L. Testing of HOT2000 version 11 in Accordance with ASHRAE Standard. eSim 2018-Building Simulation to support building sustainability, 2018, p. 1–8.

[581] Haltrecht D, Fraser K. Validation of HOT2000TM using hers BESTEST. Building Simulation to support building sustainability, vol. 97, 1997, p. 8–10.

[582] Peng Z, Jin Z, Guoqiang Z, Yezheng W. Generation of ambient temperature bin data of 26 cities in China. Energy Conversion and Management 2009; 50:543–53.

[583] Ionesco G, Balota R. Recent progress in non-residential building energy simulation software. Journal of Sustainable Energy 2013;4. doi:10.1016/j.enconman.2008.10.016.

[584] Haltrecht D, Zmeureanu R, Beausoleil-Morrison I. Defining the methodology for the next-generation HOT2000- simulator. Proceedings of Building Simulation'99., 1999, p. 61–8.

[585] O'Brien W. Nevelopment of a solar house design methodology and its implementation into a design tool. Concordia University, 2011.

[586] Naidj JS. A comparative study of passive solar building simulation using HOT2000, TRNSYS14, NETSPEC. Trent University, 1998.

[587] Attia SG, Herde A De. Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools. Proceedings of Building Simulation 2011:12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November., Sydney: 2011, p. 94–101.

[588] Horowitz S, Maguire J, Tabares-Velasco PC, Winkler J, Christensen C. EnergyPlus and SEEM Modeling Enhancements via Software-to-Software Comparison Using NREL's BEopt Test Suite. Golden, CO (United States): 2016. doi:No. NREL/TP-5500-65858.

[589] Mahmud K, Amin U, Hossain MJ, Ravishankar J. Computational tools for design, analysis, and management of residential energy systems. Applied Energy 2018; 221:535–56. doi:10.1016/j.apenergy.2018.03.111.

[590] Anderson R, Christensen C, Horowitz S. Program design analysis using BEopt building energy optimization software: Defining a technology pathway leading to new homes with zero peak cooling demand (No. NREL/CP-550-39821). Golden, CO (United States): 2006.

[591] NREL. National Residential Efficiency Measures Database | Department of Energy 2021. https://www.energy.gov/eere/buildings/national-residential-efficiency-measures-database (accessed May 1, 2021).

[592] Govt. BC. Summary of Changes to the BC Energy Step Code Part 9 Residential Buildings BC Building Code 2018 Revision 2 2019.

[593] Climate OneBuilding. Climate OneBuilding Repository of free climate data for building performance simulation 2020. http://climate.onebuilding.org/default.html (accessed April 11, 2020).

[594] Environment Canada. Canadian Climate Normals 1981-2010 Station Data 2020. https://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html?searchType=stnName&txtStationName=kelowna&searchMethod=contains (accessed April 11, 2020).

[595] Government of Canada. Canadian Climate Normals 2020. https://climate.weather.gc.ca/climate_normals/index_e.html (accessed November 17, 2020).

Appendices

Appendix A Financial Incentives

Table A1 Loan incentives

Sector	Program Name	Provider	Source	Province	Amount (CA$)/Type/Interest	Ref.
Commercial/ Institutional	Religious Buildings Initiative	Manitoba Hydro - Power Smart for Business	Utility	MB	$5,000 5 years 6.75%	[566]
	Energy Retrofit Loans	City of Toronto	Municipality	ON	20 years	[113]
Residential	CMHC Green Home	Canada Mortgage and Housing Corporation (CMHC)	Federal government	All	25 % Premium Refund	[109]
	Energy-Efficient Housing Program	Genworth Financial Canada	Private Insurance Company	All	15 % Premium Refund	[567]
	Central or ductless heat pump loans	FortisBC - Electricity - For Homes	Utility	BC	$6,500 10 years 1.9%	[568]
	RBC Energy Saver™ Loan	RBC Royal Bank	Bank	BC	>$5,000 10 years 1.0%	[110]
	Power Smart Residential Loan	Manitoba Hydro	Utility	MB	$7,500 5 years 4.8%	[114]
	Residential Earth Power Loan - for Cold Climate Air Source Heat Pumps		Utility		10,000 5 years 4.9%	[569]
	Residential Earth Power Loan - for Solar Water Heaters		Utility		7,500 5 years 4.9%	
	takeCHARGE Energy Efficiency Loan Program (EELP)	Government of Newfoundland and Labrador and takeCHARGE	Utility	NL	$10,000 5 years 4.95%	[570]
	Home Energy Loan Program (HELP)	City of Toronto	Municipality	ON	$75,000 15 years 3.5%	[111]
	ENERGY STAR® Loan Program	SaskEnergy	Utility	SK	$15,000 5 years 6.5%	[112]
	Home Repair Program	Yukon Housing Corporation	Provincial	YT	$50,000 15 years 1.0%	[571]

Table A2 Tax incentives

Sector	Program Name	Provider	Source	Province	Amount (CA$)/Type/Interest	Ref.
Residential	Home Energy Loan Program (HELP)	City of Toronto	Municipality	ON	$75,000 15 years 3.5%	[111]
	RénoVert Tax Credit	Revenu Québec	Provincial	QC	Up to $10,000	[126]

Table A3 Grant incentives

Sector	Program Name	Provider	Source	Province	Amount (CA$)/Type/Interest	Ref.
Commercial/Institutional	Grant for an Infrared Heating System	Énergir	Utility	QC	Up to $500 per appliance	[149]
	Grant to Encourage Energy Innovation				Up to $250,000 demonstration project	
	Grant for a Solar Air Preheating System				Up to $200,000	
	Grant for a Unit Heater				Up to $1,700 per appliance	
	Implementation of Energy Efficiency Measures Grant				Up to $100,000	
	Condensing Boiler Grant				Up to $25,000	
	Recommissioning Grants				Up to $100,000	
	Feasibility Studies Grant				Up to $50,000	
	Energy-Efficient Renovations Grant				Up to $100,000	
	New Efficient Construction Grant				Up to $275,000	
	Solar and Wind-powered Pump Grant	SaskPower	Utility	SK	Not Specified	[572]
Residential	Empower Me	FortisBC - Natural Gas - For Homes	Utility	BC		
	Home Energy Low-Income Program (HELP)	Efficiency PEI	Utility	PE	Varies	[131]
	Tankless Water Heater Grant	Énergir	Utility	QC	$400	[149]
	Smart Thermostat Grant				Up to $100	
	Hot Water Boiler Grants				$1,200	
	Combo System Grant				$500	
Residential+ Commercial/Institut	High-Efficiency Water Heater Grant	Énergir	Utility	QC	Not Specified	[149]

Table A4 Summary of publications on FI used in GB

No.	Focus Area	Location	Incentive	Perspective	Effectiveness/Amount	Key Findings	Limitations	Ref.
1.	Residential & Commercial	Athens, Georgia, USA	Cost reduction	Society End-users	Cost effectiveness NPV 10%-14%	The impact of cost reduction on green roofs through possible incentives yields benefits for private investors as well as society	Actual incentives were not analysed, but cost – reduction were tested through a sensitivity analysis on the basis of which future incentives can be planned	[43]
2.	Ground source heat pump [1] (GSHP) Residential	USA	Tax credit	Government	Providing 30% federal tax on GSHP increases the adoption to 30% of houses and reduces PBP 4.8 years	Spatial and economic constraints were defined to determine the suitability of GSHP and were seen to be very low (only 10% for case study)	The study was performed for putting GSHP in an existing house. As cost vary for a new house, further study needs to be performed	[51]
3.	Solar Water Heaters[1]	27 cities in China	Subsidy	Government (National)	Environmental effectiveness 0.305-0.744 CNY/kW h	Panel data model was used that calculate effectiveness that included savings of energy bills, IRR and payback periods of Solar water heaters. It was seen that the current subsidies were in-effective	Detailed subsidies for different kinds of consumers such as urban residents, public institutions and industries with boilers are suggested or future research	[53]
4.	CHP System [1] (hospital, office, hotel building, secondary school building)	11 different states USA	Capital cost Rebate Tax credits Tax loan Utility credits	Not specified	Grant > 400/kW or with Production incentives > 0.1/kWh are effective for CHP systems	Effectiveness determined through percentage payback period reduction For the majority of cases FIs tested are effective but useless in some cases and require additional action to apply CHP systems in buildings.		[54]
5.	Households ENERGY STAR appliances	The U.S.A.	Rebates	Utility	Environmental effectiveness	Cost rebates on energy star clothes-washer were found to be cost-effective	Impacts of 91% of rebates available were evaluated	[75]

					$28/ per megawatt-hour $140 tonne of CO_2 saved	Dollar increase in rebates increases the adoption rates by 0.4% only for clothes washer		
6.	Refrigerators[1]	Colombia	Subsidy Rebates	Government	Penetration Levels	Use of diffusion and discrete choice models in an ex-ante analysis revealed that 75% penetrations of AC by 2032	Willingness to pay for energy-efficient refrigerator was not considered so the effects of penetration due to financial incentive may be over-exaggerated.	[77]
7.	Low-carbon Technologies (LCT)	Global	FIT Grants Tax incentives Soft loans	End-users	Qualitative (based on previous studies)	Soft loans are less effective as a stand-alone instruments to motivate the end-users to adopt LCTs as compared to FiT, subsidies and grants		[83]
8.	Building Stock	30 different countries	Multiple	Society	(Qualitative + Quantitative) Literature review of studies related to green building policy instruments	Standards for appliances, tax exemptions, labelling, building codes, demand-side management programs and energy efficiency requirements were revealed as most effective.	Literature used for the qualitative evaluation is limited due to the absence of individual instrument evaluation as well as cost-efficiency values	[127]
9.	Residential	EU Generic	Subsidy Tax credit Loans	Society	Econometric modeling	Subsidies for renovations that allow minor energy gain are ineffective and inefficient To reduce the overall energy consumption of housing by locking building energy efficiency to a particular level.	Old houses have a cultural value and special subsidies are needed to be designed for their renovation	[156]
10.	Residential	Brisbane, Australia	Rebate	Government	Max. cost to government Aus $635 millions	The model generated in this study considered financial and non-financial benefits along with interaction among different interventions options		[193]

11.	Refrigerator[1]	United States	Rebate	Society	Econometric model, choice experiment used to find willingness-to-pay	Mail in rebates on energy-star refrigerators increases uncertainty related to refrigerator quality and reduces willingness-to-pay for it.		[194]
12.	Door/Window Heating system (Residential)	Italy	Tax credits	Society	Econometric model used to determine free-riding	With presence of subsidies, window renovations can increase to more than 30% , while for heating system tax credits are not effective and free-riding is a problem	Low renovations rate made it difficult to measure tax credits impacts precisely More survey are needed for designing policies for window and heating system upgrades since the current study uses a small sample	[195]
13.	Room Air Conditioner[1]	China	Subsidy	Government	Econometric Analysis	Most economic subsidy levels for China should be 60% as compared to existing (5-15%)		[196]
14.	Multi-Sector Technological Improvements	China	Subsidy	Society	Econometric Analysis Carbon emission under different proposed scenarios can be reduced from 15.5-19.1%	Rebound effect can be reduced for energy conservation programs by the addition of clean energy subsidies and removal of fossil energy subsidies		[197]
15.	Residential	France	Tax credit	Government	Free-riding rate ranged from 40-85%	Incentives are most effective after 2 or 3 years of the start of incentive program		[198]
16.	Refrigerator Washing Machine Boilers Light bulbs	France Italy Denmark Poland	Subsidy Tax credit	Society	Refrigerators - 185$/tCO_2$ Washing Machine 190.67$/tCO_2$ Boilers -23.87 $/tCO_2$ Light Bulbs CFLs - 761.132 $/tCO_2$	Cost-effectiveness of energy measures varies with country and energy efficiency options evaluated Taxes are more cost-effective than subsidies	Effect of change in energy price and removal of less efficient devices from the market on the fuel poor segment of the population is not investigated. Spillover effects such as rebound	[212]

						Tax credit on boilers most effective for Italy and Denmark Subsidy on CFLs cost-effective in France and Poland	effect, increased sale of appliances is also not evaluated	
17.	Commercial	4 cities in China	Subsidy	Governme nt	Comparative analysis	Lighting system retrofits were seen to be most prevalent retrofit in commercial buildings. Subsidy incentives offered for educational buildings are more than the offices		[214]
18.	Energy-efficient appliances (residential)	China 22 provinces	Subsidy	Governme nt	Energy subsidy was found to be ineffective	Different factors affecting population behaviour for selecting energy efficient appliances were determined The effect of subsidy policy were vanished after 3 years of the end of policy.		[215]
19.	Residential	Switzerlan d	Subsidy Tax allowances Carbon tax	End-users	Cost effectiveness IRR ranged from energy retrofit varies from 2.1% -12.1%	All tested incentive has a positive influence on NPV and IRR, but only combination of instruments pushed the NPV into profitability Energy price is one of the most important parameter in investment analysis	Certain cost parameters such as smaller heating system, replacement of system and Willingness-to-pay for an energy upgrade were not considered, which will yield higher cost savings	[216]
20.	LCD Television[1]	Seoul, South Korea	Rebate Tax deduction	Governme nt (National)	Environmental effectiveness 21,200 tCO_2 50 GWh power saved	Combination of rebate and tax allowance on an appliance can result in a significant reduction in electric power demand and CO_2 emissions A comparison is made on financing models of Japan, the USA and South Korea and yields current program in Korea fall short on maintenance requirements.	Impacts of other products and incentives on the effectiveness were not determined. Adverse effects possible due to FIs are not considered	[217]

21.	Natural Gas Furnace[1]	Canada	Grants Tax credit	Government	Environmental effectiveness $70-110/tCO_2	Free-riding is represented by approximately 70 % of expenditures under the Canadian subsidy and tax credit programs.	Limited data used on a single equipment (furnace)	[218]
22.	Lighting and cooling equipment Commercial	USA	Multiple	Utility	Qualitative	Incentives suitable for different sizes of commercial buildings are explored	Quantitative study needs to be performed to calculate the effect of different incentive types	[220]
23.	Residential & Non-Residential	Netherlands	Subsidy Tax credit Energy tax	Policymakers	Qualitative	Energy tax is much more cost-effective than building codes Tested FIs were insufficient to reach the energy savings needed. Energy price was an important criterion for effectiveness	The study was unable to quantitatively assess the effectiveness of individual incentive nor a policy mix due to lack of data availability Other impacts resulting from FIs implementation such as housing costs, employment and others were not investigated Newer agreements within different bodies were not considered	[221]
24.	Gas Furnaces[1]	USA	Rebates	Government	Maximum Total energy savings =0.442 quads Maximum NPV=5.9 billions	A framework is proposed for evaluating energy, economic and environmental impacts of policy instruments		[222]
25.	Residential sector	France	Incentive Tax credits Interest free Loans Grants	End-users Society Utility provider	End-user B/C ratio range 0.93-3.81 Society B/C ratio range 0.30-1.39 Utility provider B/C ratio range 0.12-0.88	Cost –effectiveness is measured from 3 different perspectives It is not necessary that an energy efficiency program is beneficial from all three perspectives	Sample size and a lack of data of a control group added a degree of uncertainty to the results Spillover impact and impacts of free-riders are not accounted either	[223]

26.	Residential	Sweden	Subsidy Tax credit	Society End-users	Qualitative + Quantitative (System analysis approach plus results from previous studies)	The variation in heating systems from different suppliers had a larger impact as compared to subsidy and taxes.	Change in house value with different types of heating systems and energy prices is not investigated	[224]
27.	Residential heating systems	8 EU Countries France Germany Italy Spain Sweden Romania Poland UK	Rebates	Policy makers	Choice experiment used to determine free-riding	For 40% rebates free-riders exceeded 50% of the population in most countries Impact of weak and strong free-riders on cost-effectiveness was calculated	Study is based on the stated behaviour of upgrade Variation in heating technologies across different countries is not considered Rebound effects and administration costs, as well as hidden costs, are not accounted	[225]
28.	Residential	Estonia	Grants	(micro-economic level)	25% grant support motivated owners to invest €20/m^2 on energy renovations	Minor energy renovations are not useful and incentives should be designed to make existing apartment buildings to better energy level or building energy code.		[227]
29.	Multi-Sector	Latvia	Environme ntal Tax	Governme nt	Economic efficiency Environmental effectiveness (based on previous studies)	Low environmental effectiveness is associated with environmental taxes despite high economic efficiency		[229]
30.	Dishwasher[1]	Spain	Subsidy Tax /energy tax (disincentiv e) Subsidy + tax	End-users	Environmental effectiveness and Economic efficiency (using demand and supply models) Welfare loss €24,000-38,000 for average energy	Subsidy (rebates) increased adoption rates from 4.8-7.7% for labelled dishwashers with rebound effects Tax decreases the adoption of in-efficient appliances by 1.4-2% with no rebound effects	The rebound effect evaluated does not consider the possible over consumption energy and water with penetration of other energy efficient equipment in the market	[230]

					consumed over 10 years Energy bills €192,425-260,902	Tax + Subsidy increases adoption of labelled 0.5-1.2%	Welfare impacts as well as interaction with other subsidy, tax allowances etc. are not taken into consideration	
31.	Solar Panels and solar hot water (Residential)	Brisbane, Australia	Rebates	Society	≈30t/yr	The study estimated rebate for a solar hot water heater is more cost-effective as compared to solar panels, which are preferred by high-income households Properly planned timeframe is needed for maximum penetration. If rebates are terminated 30% into the timeframe 90% of the GHG emissions savings will be lost	Non-financial benefits as well as impacts of the time frame when rebate is available were not assessed	[236]
32.	Home Appliances	Rizhao City, China	Subsidy	Society	Electricity consumption logarithmic difference Urban areas=4.34 Rural areas=2.86	With the application of subsidy, a significant rebound effect was seen in household electricity consumption	Consumer behaviour needs to be taken into consideration for future investigations	[237]
33.	Solar driven heat engine (Residential)	Canada	Subsidy FiT Carbon tax	End-users	Environmental effectiveness ≈0.3 $kgCO_2kWh^{-1}$	Combined use of FiT incentive and carbon tax could result in a payback period of 11.3 years for solar-driven heat engines		[238]
34.	Solar Water Heaters[1] Residential & Commercial	10 locations, Taiwan	Subsidy	Not specified	For residential buildings highest PBP for most locations is 15 years For commercial buildings highest PBP is 5.4 years	FIs for SWH are not effective for residential buildings in Taiwan Solar water heaters are more economically feasible for the commercial sector than residential As return on investment increase, people are more willing to invest in solar thermal energy		[241]
35.	PV Systems Residential	51 cities,	Rebates	Governme nt	NPV	35% of the targeted cities achieved break even point		[242]

		United States	Tax deductions Tax credit FIT		profitability index (PI) PBP			
36.	Residential	Netherlands	Subsidy Carbon tax	Program provider	Qualitative + Quantitative	The study determined interaction effect on the combined use of different policy measured and showed combinations of policy measures yielded 13–30% less effect than the sum of the effects of the separate measures.		[247]
37.	Residential heating systems	Italy	Rebates Tax credit	Society	Environmental effectiveness €279/tCO_2	Tax credits are not cost-effective Savings on energy bills are most more cost-effective as compared to the rebates on an initial investment	Impact of free-riders not evaluated	[262]
38.	Residential and Industrial	Geneva, Switzerland	VAT on electricity tariff Tax deductions	Multi-stakeholders	Cost –effectiveness B/C Ratios averages Participant 1.83 Ratepayer 0.24 Energy consumers 0.81 Program administrator 1.15 Utility 0.27 Geographic Jurisdiction 0.76 Societal on GDP 1.22	Cost-effectiveness was calculated with respect to different stakeholders Energy efficiency programs have a positive social and economic impact but can increase energy price and costs for utilities		[371]
39.	Multi-Sector	British Columbia, Canada	Carbon tax	Government	Qualitative (based on previous studies)	Provincial level emissions decreased from 5-15%, ensuring cost-effectiveness of the carbon tax. The support for tax by the public increased with time.	Impact of tax exemptions, reductions or tax credits for low-income houses is not considered, which will reduce the actual cost-	[573]

							effectiveness of the carbon tax	
40.	Residential	Vermont, USA	Subsidy Carbon tax	Society	Marginal cost analysis	Carbon taxes ad carbon limits can reduce environmental impacts for a building at a minimum cost, while subsidies and building codes are more cost-effective from society perspective		[574]
41.	Air Conditioner unit [1] Residential & Commercial	Abu Dhabi, UAE	FiT Subsidy	Governme nt	2.5Mt/CO_2 per sector by 2030	A new upfront tariff and subsidy were proposed to reduce energy usage and $CO_{2\text{ and}}$ the results were evaluated over short and long term basis		[575]
42.	PV Systems Residential	United States (2002-2012)	Rebates Tax incentives Solar renewable energy credits	Governme nt	500W/ US$ per 1000 residential customers	Cash rebates on solar renewable are much more effective than tax incentives	The variation in incentives with the change in rates of installation or	[576]
43.	Office Building	Pretoria, South Africa	Tax Incentive	End-users	Genetic algorithm optimization model to determine the impact of tax incentive	Tax incentive had little impact on the payback period of building energy efficiency retrofit	Only one type of incentive was considered	[577]
44.	Heat pumps[1]	Netherlan ds	Tax incentives	Policymak ers	Demand response module	Ad valorem tax are 3.5 times more effective than per-unit tax		[578]

Appendix B Energy Tools

B.1 HOT2000

HOT2000 is used extensively for the design and certification of low-rise residential buildings in Canada [309]. HOT2000 is a grey-box program that uses a series of coupled time-dependent steady-state models to determine the energy demands of the house [579].This tool uses a modified bin based method and long term monthly weather files for determining the energy performance of the residential buildings [580,581]. In the bin method, loads of the house are determined by utilizing steady-state models that are based on the assumption that the temperature remains the same within each interval and the loads can be expressed as linear functions of outdoor temperatures [582,583]. HOT2000 divides the house into three energy zones (i.e. attic, main floors and basements) and uses Alberta Air Infiltration Model (AIM2) and Mitalas method to determine the monthly and annual energy loads [584]. AIM2 model evaluates the infiltration and interaction of wind and stack effects with mechanical ventilation. The infiltration is found by the pressure difference in the windward side of the house and indoors. Hence, all the possible openings that can cause infiltration are accounted for in the model [585]. Mitalas method calculates heat losses from the foundation to the soil. It is also capable of accounting for the seasonal variation in soil temperature that affects heat losses as well as the impacts of insulation configurations [581,586].The tool also considers the impact of internal heat gains and solar transfers among the three zones for calculating heating and cooling loads. HOT2000 uses part load factors and on and off cycles to determine the size of the heating system [584]. The tool tests the energy performance using monthly steps and, owing to its steady-state nature, cannot be readily used for dynamic simulations such as a change in the solar system and wind energies. Despite its limitation as giving loads in monthly time steps, the tool is a good predictor of annual net energy performance and is periodically upgraded and tested with other tools for validation [585,586].

B.2 BEopt

Building Energy Optimization Tool (BEopt) is a graphical user interphase (GUI) focusing on residential buildings in North America and uses EnergyPlus as a simulation engine [396,397]. BEopt provides good modeling capability of house plans though its 3D modelling capacity is limited [398].The occupancy profiles are based on the number of bedrooms assigned to the model. The energy models constructed in BEopt can determine annual energy consumption and supports different levels of data-input that makes the adaptability of the tool high [587]. The tool uses Alberta Air Infiltration Model (AIM2) and enhanced ASHRAE infiltration models for air leakage calculations [588].AIM2 model evaluates the infiltration and interaction of wind and stack effects with mechanical ventilation. The infiltration is found by the pressure difference in the windward side of the house and indoors. Hence, all the possible openings that can cause infiltration are accounted in the model [585]. In addition, the Domain Model is used as the foundation for evaluating ground heat exchange and the building. Compared to the Mitalas method (that is based on two-dimensional heat exchanges), the Domain model is limited to one-dimensional heat exchange [588].The tool is capable of performing cost-based optimization and calculating energy generation on-site using renewable energy sources [589].The tool makes use of a sequential search-optimization technique that can help determine optimal and near-optimal solutions in a short time [590]. In addition, parametric analysis can also be performed to assess the impact of individual energy systems. The cost is calculated based on utility rates, incentives (tax credits and rebates) on energy systems and capital costs of energy measures. The cost data present in the tool is based on and National Residential Efficiency Measures Database of the United States [591]. All these values can be manually updated based on local databases to determine optimal energy measures.

Appendix C Calibration Benchmarks

Table C1 Calibration Benchmarks [282,311]

Calibration	Metric	Acceptable Value (%)
Monthly	MBE[a]	≤+5
	CV (RMSE)[b]	+15
Hourly	MBE[a]	≤+10
	CV (RMSE)[b]	30

[a] MBE: Mean Bias Error
[b]CV (RMSE): Coefficient of Variation of Root Mean Square Error

Appendix D Energy Rates

Table D1 Detail of Natural Gas Rates [320]

	Parameter	Value
Delivery charges	Basic daily charge	30 days at 0.4085 CA$/day (*0.29* US$/day)
	Delivery	4.296 CA$/GJ (*3.09* US$/GJ)
Commodity charges	Storage and transport	0.758 CA$/GJ (*0.54* US$/GJ)
	Cost of gas	1.141 CA$/GJ (*0.82* US$/GJ)
Other charges and taxes	Municipal operating fee	3.09% of [a] amounts
	Carbon tax	1.7381 CA$/GJ (*1.25* US$/GJ)
	Clean energy levy	0.40% of [a] amounts
	GST	5% of [b] amounts

[a] Delivery charges +Commodity charges
[b] Municipal operating fee + Carbon tax

Table D2 Detail of Electricity Rates [320]

Parameter	Value
Basic daily charge	30 days at 0.4085 CA$/day (*0.29* US$/day)
Electricity used Block 1: 1,600 kWh	9.845 CA¢/ kWh (*7.1*US¢/kWh)
Electricity used Block 2: > 1,600 kWh	15.198 CA CA¢/ kWh (*10.90* US¢/kWh)
GST	5% of a amounts

[a] Basic Customer charge + Electricity used charges

Appendix E Annual Energy Demand Reduction with EPUs

Table E1 Annual energy demand reduction with EPUs

	Occupancy Profile 1	Energy savings (%)	Occupancy Profile 2	Energy savings (%)
Initial Energy Demand	119.33GJ/yr		105.62 GJ/yr	
<10%	LED	1		
	RF	2		
	WL LED	3		
	RF LED	3		
	DHW	4		
	RF WL LED	5		
	LED DHW	5		
	WL DHW	6		
	RF DHW	6		
	WL LED DHW	7		
	RF LED DHW	7		
	PV	8		
	RF WL DHW	8		
	LED PV	8		
	RF WL LED DHW	9		
	WL PV	9		
	RF PV	10		
	WL LED PV	10		
	RF LED PV	10		
10-20%	RF WL PV	11	RF	16
	DHW PV	12	WL	17
	RF WL LED PV	12	RF WL	17
	LED DHW PV	12	LED	18
	WL DHW PV	14	RF LED	19
	RF DHW PV	14	WL LED	19
	WL LED DHW PV	14	RF WL LED	20
	RF LED DHW PV	14	DHW	20
	FN LED DHW PV	15		
	RF WL DHW PV	16		
	RF WL LED DHW PV	16		
	RF FN LED DHW PV	17		
	WN LED DHW PV	18		
	RF WN LED DHW PV	20		
20-40%			RF DHW	21
			WL DHW	21
			RF WL LED APP PV	21
			RF WL DHW	21
			LED DHW	22
			RF LED DHW	23
			WL LED DHW	23
			RF WL LED DHW	24
			PV	25
			RF PV	26

			WL PV	26
			RF WL PV	26
			LED PV	27
			RF LED PV	28
			WL LED PV	28
			RF WL LED PV	29
			DHW PV	29
			RF DHW PV	30
			WL DHW PV	30
			RF WL DHW PV	31
			FN LED DHW PV	31
			LED DHW PV	31
			WN DHW PV	31
			RF FN LED DHW PV	32
			WL FN LED DHW PV	32
			RF LED DHW PV	32
			WL LED DHW PV	32
			WL WN DHW PV	32
			RF WL FN LED DHW PV	32
			RF WL LED DHW PV	33
			RF WL WN DHW PV	33
			WN LED DHW PV	34
			RF WN LED DHW PV	34
			WL WN LED DHW PV	35
			RF WL WN LED DHW PV	35
>40%	LED HVAC DHW	59	LED HVAC DHW PV	68
	RF LED HVAC DHW	61	RF LED HVAC DHW PV	69
	LED HVAC PV	63	RF WL LED HVAC DHW PV	70
	RF WL LED HVAC DHW	63	WL LED HVAC DHW PV	71
	RF LED HVAC PV	65		
	HVAC DHW PV	66		
	RF WL LED HVAC PV	67		
	LED HVAC DHW PV	67		
	WL HVAC DHW PV	68		
	RF HVAC DHW PV	68		
	RF LED HVAC DHW PV	69		
	WL LED HVAC DHW PV	69		
	RF WL HVAC DHW PV	70		
	RF WL LED HVAC DHW PV	71		

Appendix F BC-Energy Step Code Metrics

Table F1 BC-Energy Step Code Metrics[a] (*Source*: BC-ESC [592])

City	Code Step	ACH[b]	TEDI[c] kWh/ (m^2.year)	MEUI[d] kWh/ (m^2.year) Small SFD (Area: 69.7m^2)	Medium SFD (Area: 214m^2)	Large SFD (Area: 556m^2)	Attached Units (Area: 81.9m^2/Unit)
Vancouver (CZ 4)	Step 1	3.0	–	–	–	–	–
	Step 2	2.5	43	148	108	65	108
	Step 3	1.5	38	128	93	55	93
	Step 4	1.0	28	108	78	45	78
	Step 5	>1.0	19	83	58	30	58
Kamloops (CZ 5)	Step 1	3.0	–	–	–	–	–
	Step 2	2.5	52	158	118	75	118
	Step 3	1.5	45	143	108	70	108
	Step 4	1.0	35	118	88	55	88
	Step 5	>1.0	22	88	63	35	63
Prince George (CZ 6)	Step 1	3.0	–	–	–	–	–
	Step 2	2.5	74	173	133	90	133
	Step 3	1.5	64	153	118	80	118
	Step 4	1.0	51	123	93	60	93
	Step 5	>1.0	32	98	73	45	73

[a]Only matrices applicable to the case study homes are provided in this table. For complete list of metrics please refer to BC-ESC [592])
[b]ACH: Air changes per hour @ 50 Pa (ACH_{50})
[c]TEDI: Thermal Energy Demand Intensity
[d]MEUI: Mechanical Energy Use intensity
Note: ACH target changes with the step only; TEDI targets are influenced by location of building and step; while MEUI targets vary with archetype, location and code step

Appendix G Environmental Impacts under DBPs Control Strategies

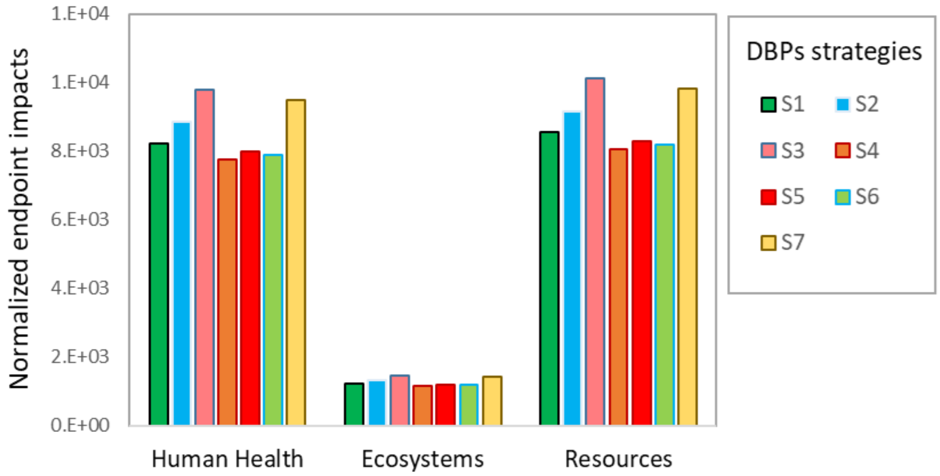


Figure G1 Comparison of endpoint environmental impacts under DBPs control strategies

Table G1 Weights for different criteria and best and worst ranking for considered DBPs control strategies

Case No.	Human Health (HH)	Ecosystems (ES)	Resources (RE)	Best Case	Worst Case
Case 1	1.0	0.0	0.0	S2	S6
Case 2	1.0	0.2	0.0	S2	S3
Case 3	1.0	0.4	0.0	S5	S3
Case 4	1.0	0.6	0.0	S4	S3
Case 5	1.0	0.8	0.0	S4	S3
Case 6	1.0	1.0	0.0	S4	S3
Case 7	0.8	0.2	0.2	S2	S3
Case 8	0.8	0.4	0.2	S5	S3
Case 9	0.8	0.6	0.2	S4	S3
Case 10	0.8	0.8	0.2	S4	S3
Case 11	0.8	1.0	0.2	S4	S3
Case 12	0.6	0.4	0.4	S4	S3
Case 13	0.6	0.6	0.4	S4	S3
Case 14	0.6	0.8	0.4	S4	S3
Case 15	0.6	1.0	0.4	S4	S3
Case 16	0.4	0.6	0.6	S4	S3
Case 17	0.4	0.8	0.6	S4	S3
Case 18	0.4	1.0	0.6	S4	S3
Case 19	0.2	0.8	0.8	S4	S3
Case 20	0.2	1.0	0.8	S4	S3
Case 21	0.0	0.0	1.0	S4	S3

Appendix H Local Annual Weather Conditions

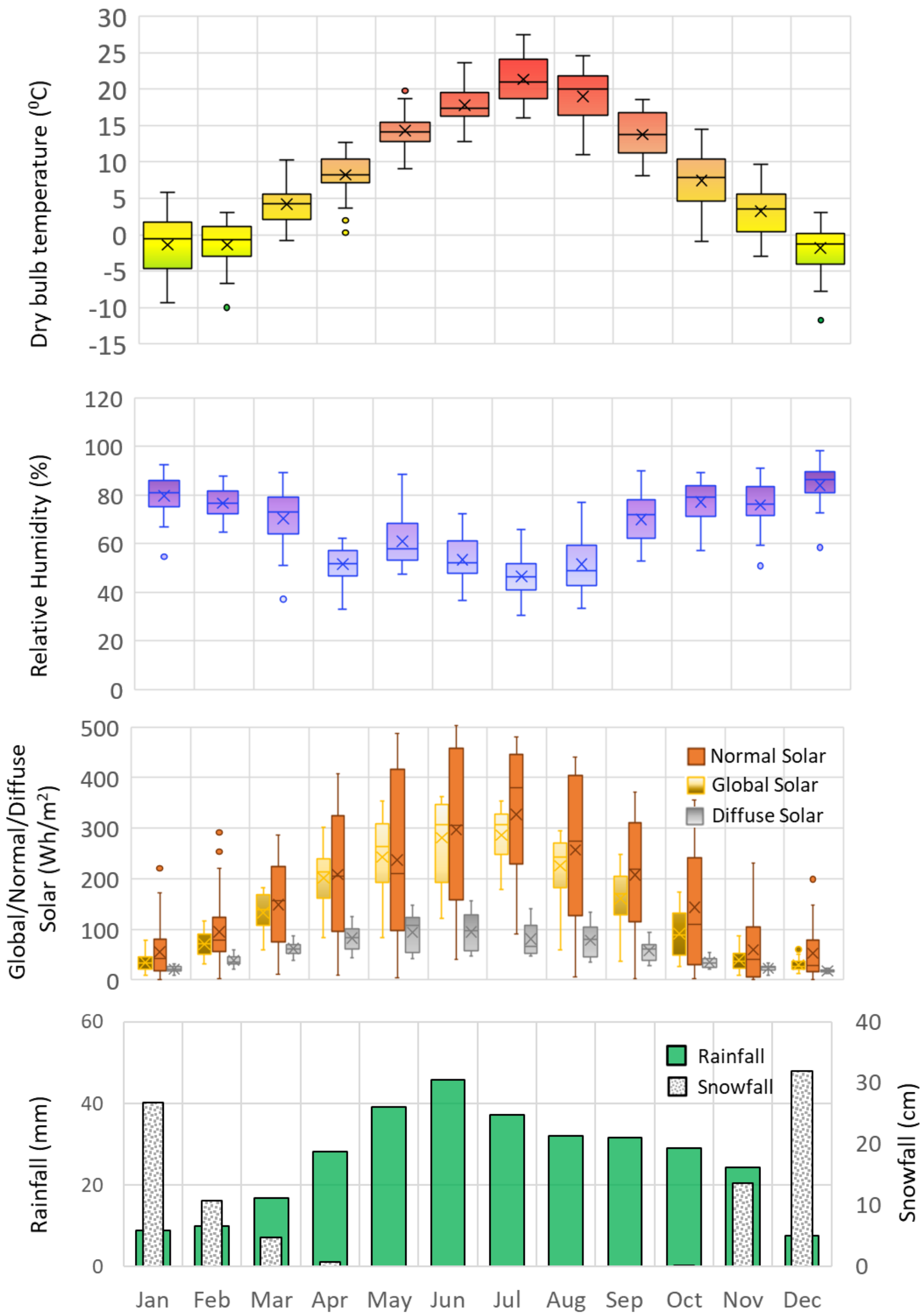


Figure H1 Local annual weather conditions in Kelowna (*Source*: [593,594])

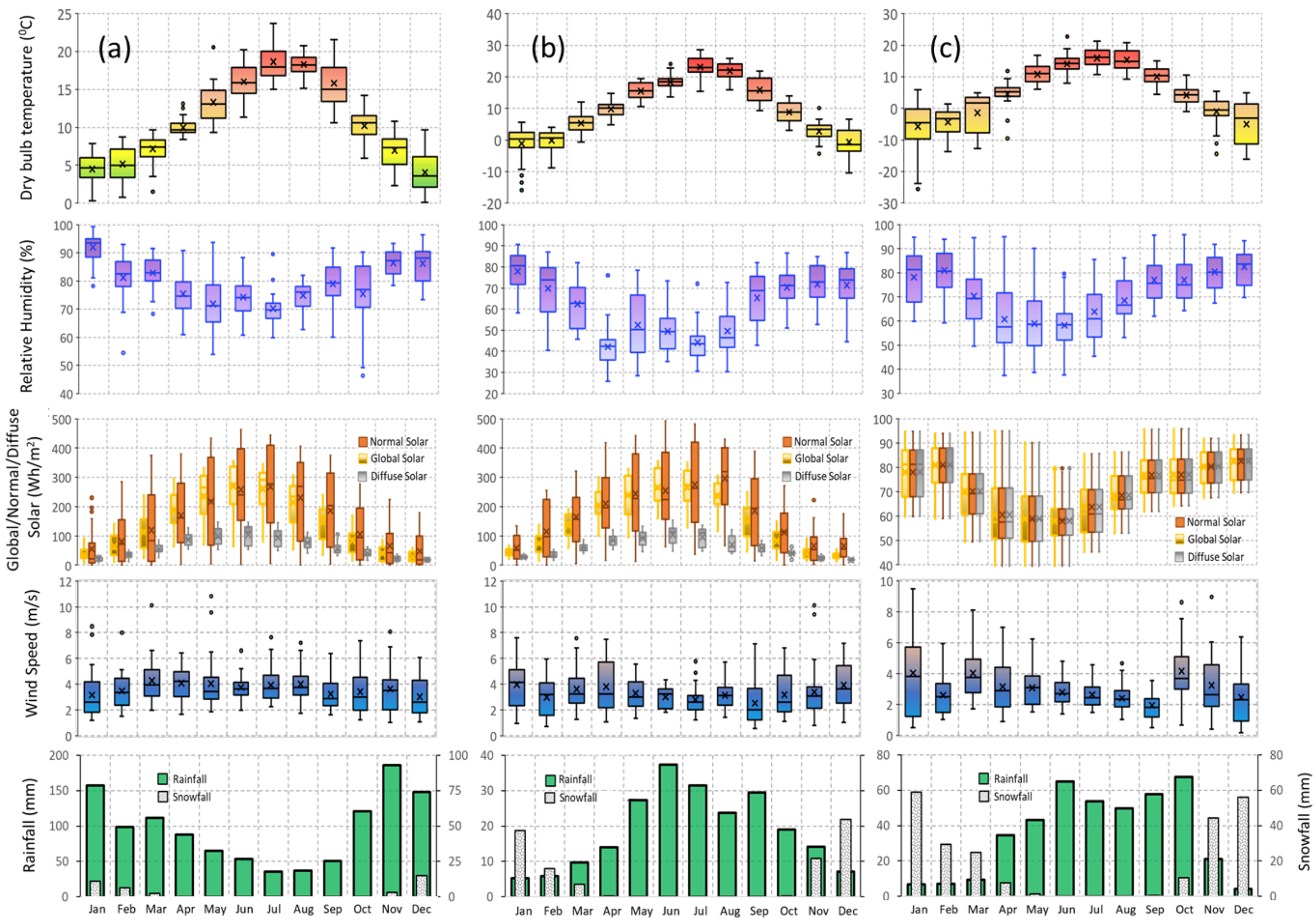


Figure H2 Local annual weather conditions in (a) Vancouver (CZ 4); (b) Kamloops (CZ 5); and Prince George (CZ 6) (*Source:* [593,595])