TOWARDS NET ZERO BUILDINGS ASSESSMENT FRAMEWORK: A NATURAL CAPITAL APPROACH

by

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Abstract

Net zero buildings can be a viable solution to the rising environmental challenges caused by the construction and building industry. Many countries around the globe are shifting toward sustainable development and net zero buildings (NZBs). Even though buildings are closely linked with their surrounding environment, consideration of local resources is largely lacking in net zero building design and assessment. This research aims to fill the knowledge gap by developing an assessment framework based on local natural capital to achieve net zero targets in buildings. The framework covers the complete life span of buildings and assesses how a building can become self-sufficient by using local natural resources. The framework aims to provide a decision support to various stakeholders in the pre-design stage, to evaluate sustainability options for implementation in the building's design.

The developed methodology is applied to a building registered with the Living Building Challenge to evaluate net zero performance over its life cycle. Impacts of each of the building components are investigated. The results indicate that the Living Building Challenge (LBC) design is not net zero, however the building can achieve net zero Carbon Dioxide Equivalent (CO_2e) emissions over its life cycle by investing more into renewable energy and with the help of materials recycling and an off-site carbon offset program.

A detailed uncertainty analysis is then performed to enhance the understanding of sustainability assessment methods. Sources of uncertainty in the developed framework are identified and different types of uncertainties are investigated. Results show that the sustainability assessment is most sensitive to the building life span, building occupants' (users') behaviours, and the end-of-life scenarios for the building materials. Based on the developed framework for net zero buildings, some policy recommendations have been made. These recommendations will guide a fair distribution of life cycle costs and benefits of net zero building among all building stakeholders.

Lay Summary

Although design, construction, and operation of buildings are in direct relation to their surrounding environment, net zero rating systems and frameworks inadequately consider regional impacts. The main contribution of this thesis is to close this research gap by developing an assessment framework for buildings that provides location specific solutions to achieve net zero targets. The developed methodology is demonstrated through a case study. Sources of uncertainty in the developed framework are identified and discussed. Results show that the sustainability assessment is the most sensitive for the building life span and building occupants' (users') behaviours. The developed framework will guide a fair distribution of life cycle costs and benefits of Net Zero Building among all building stakeholders.

Preface

I, Navid Hossaini Fard, collected and developed all contents in this thesis under the supervision of Drs. Rehan Sadiq and Kasun Hewage. My supervisors have reviewed all manuscripts and the doctoral dissertation and provided comprehensive feedback to improve these documents. Most of the content of this doctoral dissertation has been published or submitted to scientific journals, or published in reputable conference proceedings. Three journal papers and one conference proceeding directly formed the contents of this doctoral dissertation. One journal paper indirectly helped development of this thesis.

- A portion of Chapter 2 with the title "*Spatial analysis of LEED certified buildings in Canada*" was published as a conference proceeding at the World Sustainable Building 2014 Conference in Barcelona, Spain (Hossaini et al., 2014a). I conducted the analysis, wrote the manuscript, and presented at the conference. In addition, a portion of Chapter 2 was published in the Journal of Building and Environment, titled *"AHP-based Life Cycle Sustainability Assessment (LCSA) framework: A case study of 6-storey wood-frame and concrete-frame buildings in Vancouver."* (Hossaini et al., 2014b). This paper was a collaborative work and my contributions were in literature review, methodology development, data collection, performing analysis, and writing of the paper.
- Chapter 3 is based on a paper titled "*Spatial Life Cycle Sustainability Assessment: A conceptual Framework for Net Zero Buildings.*" This paper was published in the Journal of Clean Technologies and Environmental Policy (Hossaini et al., 2015). I developed the methodology, wrote the manuscript, and performed all the analysis in this study.
- A version of Chapter 4 with the title *"Path Toward Net Zero Buildings: A Natural Capital Assessment Framework"* was published in the Journal of Clean Technologies and Environmental Policy (Hossaini et al., 2017). I developed the methodology, wrote the manuscript, and performed all of the analysis in this study.

- A version of Chapter 5 titled *"Net Zero Building Policy Framework; A Game Theoretic Approach for British Columbia"* is under preparation for submission to the Journal of Environmental Management. I wrote the manuscript and performed all the analysis in this study.

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List of Abbreviations

BIM	Building Information Model
BREEAM	Building Research Establishment Environmental Assessment Method
CaGBC	Canada Green Building Council
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CLT	Cross Laminated Timber
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DOE	Department of Energy
EA	Energy and Atmosphere
EOL	End-of-Life
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Greenhouse Gases
kW	Kilowatt
LBC	Living Building Challenge
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle Energy
LCI	Life Cycle Inventory

LEED	Leadership in Energy and Environmental Design
LPF	Litre Per Flush
LPM	Litre Per Minute
M&V	Measurement and Verification
MCDA	Multi-Criteria Decision Analysis
MR	Materials and Resources
NCA	Natural Capital Assessment
NPV	Net Present Value
NZ	Net Zero
NZB	Net Zero Buildings
NZEB	Net Zero Energy Building
NZI	Net Zero Buildings Index
PV	Photo Voltaic
QMRA	Quantitative Microbial Risk Assessment
REC	Renewable Energy Certificate
SHGC	Solar Heat Gain Coefficient
USGBC	United States Green Building Council
VOC	Volatile Organic Compounds
WEM	Water-Energy-Materials
WWTP	Waste Water Treatment Plant

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This work is the result of many people's support. First and foremost, I would like to express my sincere gratitude to my advisors Drs. Kasun Hewage and Rehan Sadiq. Dr. Hewage has been an inspiration since I have known him. I am very grateful that I got a chance to work under his supervision for both my Masters and PhD at the University of British Columbia. Dr. Hewage has always believed in me and gave me encouragement to grow as a researcher. I am extremely thankful for his wisdom, patience, kindness, vision, and passion for research. Dr. Sadiq is an exceptional mentor and an outstanding professor. His hard work, passion for success, and research vision inspired me to never give up and always try to improve. I am deeply grateful for his guidance and trust in my abilities.

I am very thankful to Dr. Shahria Alam and Dr. Ahmad Rteil for being part of my doctoral committee. Dr. Alam and Dr. Rteil have provided insightful comments on my research and kindly supported me during my doctoral studies.

I am thankful for the support and help provided by my colleagues at the Project Lifecycle Management Laboratory at the University of British Columbia. I appreciate the kind support of Haibo Feng and Rajeev Ruparathna.

I am grateful to the Natural Sciences and Engineering Research Council (NSERC) for providing financial support for this research through the Alexander Graham Bell Canada Graduate Scholarship (CGS-D). I would like to thank Okanagan College for providing data to undertake this research study. I would like to thank the amazing people of Recollective Consulting for all of their support and help during my doctoral study: Eesmyal Santos-Brault, Jason Packer, Erica Letchford, Tim Tewsley, Selena Schroeder, Jay Burtwistle, Chris Kendall, and Eleanor Kroeger.

I would like to thank my dear family who have provided unconditional love and support while I have been away from them. I am forever grateful to my mom and my dad for their care throughout my life, for all of their prayers, and for teaching me to be a good person. I am exceptionally thankful for the support and positive energy I received from

my brothers, Hamid and Vahid. I can't thank God enough for having them in my life. Hamid and Vahid are true role models whom I learn from every day.

Finally and most importantly, I am forever grateful to my wife and better half, Atousa. This PhD would not have been possible without all of the unconditional love, kindness, positive energy, insights, and encouragement I received from her during this journey. She made every step of the way enjoyable and unforgettable. Atousa showed me the light at the end of the tunnel, taught me to work hard, dream big, and to believe in myself. I am extremely happy and excited to continue this incredible journey with her.

To my better half, Atousa

Chapter 1. Introduction

1.1 Background

Buildings, in different forms, have always been part of the human race. They have been shelter, provided comfort, and protected humans from the dangers of the surrounding environment. The primary purpose of buildings has not changed over time, but the methods and impact of construction have significantly evolved in the last century.

Consequently, impacts of building and the construction industry on environment, society, and economy have increased significantly. The building sector produces the largest amount of CO_2 emissions, more than the industrial sector (Energy Information Administration, 2006). The building sector is responsible for 40% of raw materials consumption (US Green Building Council, 2015) and around 40% of total energy consumption (US Energy Information Administration, 2017). Buildings also account for 45 to 60% of landfilled waste generated (U.S. Green Building Council USGBC, 2007).

From an economic perspective, the building sector has a considerable share in gross domestic product (GDP) of both developed and developing countries. The Canadian construction industry contributes about 6% of Canada's GDP, which has grown more than 40% in the last decade (Statistics Canada, 2011). Similarly in Australia, the construction industry contributes 7.5% to the GDP (Zuo and Zhao, 2014). The portion of construction in GDP is even higher in developing countries, such as Armenia (19%), Tajikistan (11%), and Romania (10%) (UNECE, 2010). This is due to the need for building infrastructures.

From a social perspective, people are in constant interaction with buildings by spending most of their time in indoor environments. The U.S. Environmental Protection Agency (2017) study shows that North Americans spend 90% of their time indoors. This exposure means that indoor environmental quality has a direct impact on occupants' health, well-being, and productivity.

Due to increasing environmental challenges such as global warming, resource depletion, and waste generation, much research has been conducted in the past two decades on the impact of buildings, and the need to move toward green buildings. Green buildings have a lower environmental impact compared to traditional buildings by consuming less energy and water, but they still rely on the grid for energy and water supply. There are various definitions for green buildings (also referred to as sustainable buildings). Yudelson (2008) defined a green building as a "high-performance property that considers and reduces its impact on the environment and human health." A widely accepted definition of a green building is provided by the United States Environmental Protection Agency (US EPA) as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction" (US EPA, 2010).

With research advancements in building sciences and construction engineering, a new theory in the sustainability of built environment was developed. This theory goes beyond traditional green building targets and focuses on self-sufficient buildings or Net Zero Buildings (NZB). A Net Zero Building is a building system that uses sustainable materials and produces its needed energy and water throughout its life cycle (Hossaini et al., 2015).

Building and construction industries are responsible for a considerable portion of environmental impacts; hence there is a need for a paradigm shift from some of the traditional construction practices, which can be harmful to the surrounding environment. The Net Zero Building is a viable solution for this challenge. With recent successes in engineering and building science research, the net zero theory is no longer considered an idea for future generations to explore but a realistic solution to mitigate carbon emissions and to reduce energy use in the building sector for the current generation (Marszala et al., 2011).

Many countries around the globe are realizing this fact and are setting goals to achieve net zero targets in buildings. The United States passed an Act to support the goal of net zero energy for all new commercial buildings by 2030 (EIA, 2006). Similarly, the EU established the Nearly Zero Energy Building as the target for 2018 for all publicly owned buildings, and for 2020 for all new buildings (EPBD, 2010). In Canada, the government goal is to develop and adopt a net zero energy ready model building code by 2030 (Government of Canada, 2017).

Design and operation of Net Zero Buildings require careful consideration of the building's surrounding environment and available resources. If selected building systems and materials are not in harmony with the environment, the building will not achieve the net zero goal. Also, the economic cost of Net Zero Buildings can create an obstacle for all stakeholders. Therefore, it is necessary to carefully assess life cycle impacts of Net Zero Buildings from both environmental and economic aspects.

In summary, design and operation of Net Zero Buildings require attention to natural capital and assessment of available technologies and resources at the location of building. A robust NZB assessment framework that is capable of evaluating the environmental and economic performance of a building, and that provides decision support to achieve net zero, can help building stakeholders move toward sustainable development. A decision support framework is an adaptive outlined process that helps stakeholders achieve specific objectives and guides them toward an optimal solution (Karmperis et al., 2013).

1.2 Research Gap

Sustainability of the built environment is assessed using building rating systems. The majority of building rating systems and assessment frameworks are developed for green buildings and only a small portion of them are capable of analyzing Net Zero Buildings. Among all of these sustainability assessment frameworks, the Living Building Challenge (LBC) is the only rating system requiring net zero targets for buildings (Bendewald & Zhai, 2013); however the Living Building Challenge has major shortcomings. Similar to Leadership in Energy and Environmental Design (LEED) as well as a majority of other building assessment frameworks, Living Building Challenge is simply a list of performance requirements within a defined set of categories (Cole, 2010). Living Building Challenge lacks a clear methodology on how a building can achieve the performance requirements set by the rating system. This assessment method ignores the embodied impact of building materials over their cradle-to-grave life cycle and only focuses on avoiding products that contain 14 red-listed substances (Atlee, 2011). The building rating system does not provide a framework or mechanism for assessing a building's potential for becoming self-sufficient by using local resources (Hossaini et al., 2015). There is a knowledge gap in the literature for linking local natural capital and NZBs.

Although design, construction, and operation of buildings are in direct relation to their surrounding environment, existing net zero rating systems and frameworks inadequately consider regional characteristics for assessment of buildings. Despite the influence that local environmental conditions have on buildings, consideration of regional resources in sustainable buildings is largely lacking in the literature (Cidell & Beata, 2009). Considering the variability of environmental behaviour around the globe and its significant effect on energy and water supply, it is a major drawback to ignore the role of 'location' in green building assessment (Eliasson, 2000).

This research study will address this knowledge gap by developing an assessment framework for buildings that provides location specific solutions to achieve net zero targets in buildings. The framework considers the full life cycle of buildings and evaluates the availability of local natural resources. The framework analyzes the resource demand of buildings and evaluates the building's ability to become self-sufficient with net zero impact.

This thesis will help building stakeholders understand the potential of natural capital, and use the concept to design, build, and operate a self-sustaining building. The research also proposes a policy model for Net Zero Buildings that provides decision support for sustainable development and can be used for urban planning and management.

An integrated framework will be developed to consider the life cycle impact of the building components throughout its life cycle. A decision support system will guide the stakeholders on potential of using natural capital for the building. The main contribution of this research is to assist stakeholders in assessment and decision making related to

NZBs at the pre-design stage of the building. NZB policy recommendations in this thesis provide a method for fair distribution of costs and benefits of NZBs among all stakeholders.

1.3 Research Objectives

The main objective of this research is to develop a natural capital based framework for sustainability assessment of Net Zero Buildings. The proposed framework considers the life cycle impacts of buildings, regional characteristics, and available natural capital to provide location specific solutions to achieve net zero targets in buildings. Energy, water, and building materials are selected as three main components of NZBs. To assist policy and decision-making, a NZB policy recommendation is made for the province of British Columbia. This NZB policy can be extended to other provinces of Canada and other countries. The developed framework aims to assist building stakeholders in the pre-design stage to evaluate sustainability options for implementation in the building's design and provides a model for fair distribution of NZB cost among all stakeholders. The proposed policy focuses on NZB; however it has the potential to be applied to other multi-stakeholder engineering projects that deal with sustainability and policy-making. Specific sub-objectives of this research are as follows:

- Sub-objective 1: Conduct a critical review of published technical articles on sustainability assessment methods, NZB systems, and natural capital.
- Sub-objective 2: Develop a life-cycle, natural capital based framework for NZBs.
- Sub-objective 3: Apply the developed framework for sustainability assessment of an LBC building in British Columbia and provide a location specific solution for achieving net zero targets. This validated framework will provide guidelines for sustainable regional planning.
- Sub-objective 4: Study the impacts of uncertainties on the solutions provided by the developed framework.
- Sub-objective 5: Use the developed framework to provide policy suggestions for NZBs in British Columbia.

1.4 Thesis Structure and Organization

Figure 1.1 shows the structure and organization of this thesis to achieve the objectives identified in Section 1.3. The thesis consists of six Chapters. Chapter 1 provides an introduction to the research question addressed in this thesis. Chapter 2 provides a critical review of the relevant literature for sustainable building assessment and identifies the research gap. Chapter 3 proposes and develops an original natural capital based framework for assessment of Net Zero Buildings. As a proof of concept, Chapter 4 applies the developed framework to an LBC building and provides a decision support for achieving net zero targets. Chapter 5 discusses the impacts of uncertainties in the parameters, models, and scenarios on the results of the developed framework and uses the developed framework to propose a Net Zero Building policy recommendation. Finally, Chapter 6 provides a summary and conclusion of the research, discusses assumptions and limitations, and presents recommendations for potential next steps.

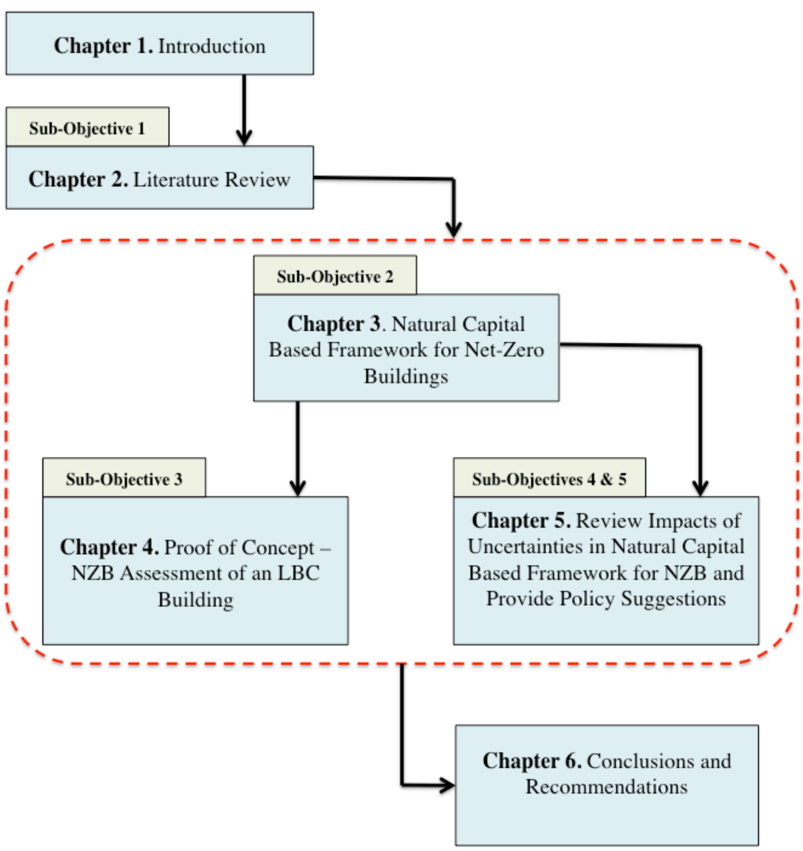

Figure 1-1 Thesis structure and objectives

Chapter 2. Literature Review

This chapter contains the state-of-the-art literature related to this research and identifies drawbacks of current NZB assessment methods. The chapter includes background information on different types of sustainable buildings, sustainable building rating systems and assessment frameworks, natural capital assessment, and regional considerations in green and NZBs. This review shows that there is a knowledge gap in terms of a comprehensive NZB assessment framework that provides location-specific solutions for each building and can assist building stakeholders for sustainable development.

2.1 Sustainable Buildings

Sustainable buildings can be categorized into three groups: green buildings, near-zero buildings, and NZBs. This section provides a background for each group of buildings.

2.1.1 Green Buildings

The United States Environmental Protection Agency (US EPA) defines green buildings as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction" (US EPA, 2010). There have been many studies to investigate the benefits of green buildings over conventional buildings in three categories: environmental benefits, economic benefits, and social benefits.

Roodman and Lenssen (1995), US DOE (2007), (USGBC, 2017), Akadiri and Olomolaiye (2012), Yeheyis et al. (2013), and Hossaini et al. (2014a) discussed the environmental benefits of green buildings and mainly focused on source reduction benefits of green buildings. Compared to conventional buildings, green buildings consume less water and energy. The economist (2004), Kats (2006), and Langdon (2007) evaluated economic benefits of green buildings and highlighted that the main cost saving advantage of green buildings is due to lower energy/utility bills and higher market value for sale or rent. Petrovic-Lazarevic (2008), Abowitz and Toole (2009), Zuo et al. (2012), Zhao et al. (2012), and Hossaini et al. (2014b) studied social benefits of green buildings and concluded that green building practices result in improved health and comfort for the building occupants.

Green building targets can be achieved at both micro and macro levels. The macro level targets green building at a high level through making and enforcing sustainability policies. For example, the City of Vancouver in Canada implemented the Green City 2020 action plan that requires all new buildings applying for rezoning in the city to target the LEED Gold, Passive House, or Low Emission Green Building Policy (City of Vancouver, 2017a). On the other hand, the micro level focuses on buildings and covers the use of technology and integrated design processes to make construction and design more sustainable. Yuan et al. (2013), Li et al. (2013), Marszal et al. (2011), and Berggren et al. (2013) reviewed technologies used in green buildings. The sustainable technologies such as solar panels, low flow faucets, and low VOC paints help in achieving green building targets by conserving energy and water, and lowering human health impacts.

2.1.2 Near Zero Buildings

A clear universal definition of a Near Zero Building is not available, and it is often linked to the framework used for the building analysis (Kampelis et al., 2017). The goal of near zero buildings is to achieve better performance than green buildings and get close to being self-sufficient. Energy is the main aspect addressed in Near Zero Buildings (Marszal et al., 2011).

Some studies in the literature focused on performance of Near Zero Buildings. Kampelis et al. (2017) investigated energy performance of three buildings designed to be ‘Near-Zero Energy’ and compared the operational performance with the intended energy model. The authors concluded that the Near Zero target is largely achieved by renewable energy technologies and the implementation of advanced monitoring and controls. Other scholars focused on specific systems or components of Near Zero Buildings. Gil-Baez et al. (2017) studied natural ventilation systems in the context of Near Zero Buildings. Gandolfo et al. (2017) studied building materials’ radioactivity and radiation protection in Near Zero Buildings. Loukaidou et al. (2017) performed a cost analysis for the building envelope of Near Zero Buildings.

Near Zero Buildings are gaining popularity in Europe as the European Union (EU) established the Directive on Energy Performance of Buildings that designates the 'Nearly Zero Energy Building' as the building target for 2018 for all publicly owned buildings or those occupied by public authorities, and for 2020 for all new buildings (EPBD, 2010). The main drawback of Near Zero Buildings is that the entire focus is put on energy, and other important resources used in buildings, such as water and building materials, are not widely considered in the assessment (Chwieduk, 2013).

2.1.3 Net Zero Buildings

The 'net zero' concept is no longer perceived as a conceptual idea for the future, but as a realistic solution to mitigate CO_2 emissions and to reduce energy use in the building sector (Marszal et al., 2011). Net zero is the most rigorous performance that a sustainable building can achieve. NZB is a building system that uses sustainable materials and produces its needed energy and water throughout its life cycle. Even though buildings include a wide range of systems and components, the main components of NZBs are the energy system, water system, and building materials (Chwieduk, 2013; Anink et al., 1998).

Increasing environmental challenges, water/energy crises, and technology development are among the main reasons for increasing the research around the NZB concept. Also, various governments are setting goals to achieve net zero targets in buildings. For instance, the United States within the Energy Independence and Security Act of 2007 (EIA, 2006) authorizes the Net Zero Energy Commercial Building Initiative to support the goal of net zero energy for all new commercial buildings by 2030. It also specifies a zero energy target for 50% of U.S. commercial buildings by 2040 and net zero for all U.S. commercial buildings by 2050 (Crawley et al., 2009).

Table 2-1 shows the most recent studies related to NZBs in the literature. These studies were published in peer-reviewed journals between 2013 and 2017 (5 years).

Table 2-1 NZB literature review

Reference	Objective and Strength	Limitations and Weakness
Berggren et al. (2013)	Life Cycle Energy (LCE) analysis of NZB. Authors analyzed the increase of embodied energy compared to the decrease of the building operation energy use. Results showed that moving from a low energy building to a NZB results in only a small increase of the embodied energy.	The entire focus of this paper is on energy component of NZB, and other main systems such as water and building materials are excluded from the study.
Zeiler and Boxem (2013)	Net Zero Energy School. Authors performed an energy analysis for a net zero energy school in the Netherlands and results were compared with conventional schools.	Authors selected energy as the only component of net zero buildings. In addition, the focus of study is only on the operational phase of the school, not the entire life cycle.
Thomas and Duffy (2013)	Authors investigated the energy performance of twenty net zero energy homes and near net zero energy homes in New England region of the United States. They found that even in cold climate of New England these homes could meet or exceed their intended design energy performance.	Similar to the above studies, authors focused only on energy performance as the indicator of net zero buildings. The energy consumption associated with construction phase and end of life is not captured in the analysis.
Jin et al. (2014)	This paper presented a framework system to assess feasibility of a net zero energy house design for Northern China. The energy performance is as simulated and monitored during operation for comparison.	As noted by the authors a holistic life cycle approach is not considered in this paper. Authors concluded that "To achieve a really zero energy house, a life cycle analysis should be set up to assess the whole performance of the house."
Pan (2014)	Pan developed a theoretical model of the system boundaries of zero carbon buildings. Pan considered life cycle approach in his framework. The framework is used for assessment of five zero energy or carbon buildings.	The developed framework is theoretical and qualitative. It does not allow for quantitative assessment and comparison of net zero buildings. Water consumption is excluded from theoretical model and its role in NZB is ignored.

Reference	Objective and Strength	Limitations and Weakness
Dang et al. (2014)	Authors conducted literature research on how to evaluate a performance of net zero energy building (NZEB). A list of widely used research methods, tools, and performance indicators for net zero evaluation is provided.	Similar to the studies noted above, the entire focus is on energy performance during operation phase of the building. Authors acknowledged the importance of LCA in NZB assessment and noted that "The LCA application in NZEB evaluation performs an unavoidable update in NZEB definition and the related evaluation methodology. More works on such research directions are needed so that a more comprehensive evaluation framework can be established with the development of evaluation tools, indicators, etc."
Zhao and Pan (2015)	Authors have developed a conceptual framework of business models for zero carbon buildings. The result was presented using a case study. The main objective of the paper was to present the business potentials of zero carbon buildings to accelerate the uptake of this group of buildings.	The entire focus of this conceptual framework is on the economic benefits of zero carbon buildings, and environmental performance is excluded from the assessment. The framework lacks quantitative metrics or methodologies to calculate the economic performance of buildings.
Giordano et al. (2015)	The authors assessed operational energy and embodied energy of two residential Nearly Zero Energy Buildings.	The paper does not provide a clear methodological framework for energy assessment of near zero or net zero buildings. The study is limited to presentation of energy results of the two case study buildings.
Sorensen et al. (2017)	Authors evaluated the actual energy performance of a zero emission office building during its first year of operation and noticed a very good correspondence with the planned energy budget.	The study lacks a structured methodological framework to apply to other net zero buildings. LCA is ignored and only operational energy is considered in the assessment.

Reference	Objective and Strength	Limitations and Weakness
Goggins et al. (2016)	Authors have conducted a cradle to grave life cycle environmental and economic assessment of nearly zero energy buildings in Ireland. The main focus is on high performance thermal and airtight building envelope. Authors have found that near zero energy buildings can be cost effective compared with conventional buildings.	The emphasis of the study is on energy performance, and building materials and water systems are excluded from the analysis. The methodology used in the paper is not presented in a framework to be used in other regions.
Zhou et al. (2016)	Authors studied the actual operational performance of a "net zero energy building" in China. They noted that the vast majority of studies in the literature focus on theories and simulation, and actual performance during occupation has been largely overlooked.	The study lacks a clear methodological framework for assessment of net zero buildings over the entire life cycle. The renewable energy consideration is limited to solar energy (through PV systems), and other renewable energy forms such as wind and geothermal are not considered.
Florentin et al. (2017)	Authors performed a life cycle energy and carbon analysis of 'hemp-lime' bio-composite building materials and found that this material has a clear advantage over conventional building materials in terms of embodied and operational CO_2 emission.	Authors selected only one sustainable building material for their assessment. Water footprint of the material is not included in the analysis.
Yi et al. (2017)	Authors used emergy theory to evaluate the sustainability of NZEB. Results showed that NZEB uses greater non-renewable emergy to achieve a zero-energy budget.	Even though the study analyzed the building from a holistic life cycle lens, the focus is only on energy. Building materials that are shown to have a considerable environmental footprint are excluded from the scope.

The main focus of these studies is performance analysis of NZBs. The majority of these research studies emphasized energy as the main component of NZBs and ignored the impact of building materials and water consumption in their analysis. Another limitation of these studies is the 'period of assessment'. The vast majority of current literature focuses on the operation phase and ignores the life cycle embodied effects of building systems and materials.

2.2 Sustainable Building Rating Systems and Assessment Frameworks

Sustainable building rating systems and assessment frameworks are sets of criteria used to evaluate buildings in terms of sustainability. These assessment frameworks can be categorized into three groups: those that focus on green buildings, those that focus on near zero buildings, and those that focus on NZBs.

2.2.1 Green Building Assessment Frameworks

A number of assessment rating systems have been developed to measure the sustainability level of green buildings. The leading building rating systems include BRE environmental assessment method (BREEAM), Leadership in Energy and Environmental Design (LEED), Green Star, and Comprehensive Assessment System for Built Environment Efficiency (CASBEE). These rating systems evaluate buildings against a set of pre-defined sustainability criteria such as energy consumption, resource use, and indoor environmental, in a point-based system. The sustainability level of the building is then evaluated based on the number of points it achieves according to these criteria. Chew and Das (2007), Pulselli et al. (2007), Haapio and Viitaniemi (2008), Hossaini (2012), and Zuo and Zhao (2014) reviewed green building rating systems and identified that the main limitation of these rating systems is 'point chasing', where buildings target easy-to-achieve points and ignore the more critical points related to energy efficiency, water efficiency, and resource conservation. These rating systems do not consider the full life cycle of buildings in their assessment.

The following sections provide a review of LEED and BREEAM. LEED is the leading green building rating system in North America and BREEAM is the leading environmental assessment method for green buildings in Europe.

2.2.1.1 LEED

Leadership in Energy and Environmental Design (LEED) is the most widely adopted building rating system in North America. LEED, developed by the United States Green Building Council (USGBC) in 2000, is a point-based building rating system. The current version of this rating system, LEED v4 (USGBC, 2017), has a total of 110 points consisting of 100 base points, 6 possible points for innovation, and 4 regional priority points. A building will be evaluated against the following six main categories:

- Location and Transportation
- Sustainable Sites
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources
- Indoor Environmental Quality

Based on the number of points achieved in each category, the building receives one of four levels of certification:

- Certified 40–49 points
- Silver 50–59 points
- Gold 60–79 points
- Platinum 80 points and above

Despite its popularity, the LEED framework has major weaknesses in measuring true sustainability performance of the built environment. The point-based nature of the framework can lead to point hunting, where non-relevant points are targeted without addressing major issues such as energy conservation or water efficiency (Chew & Das, 2007). A research study based on analyzing 100 certified buildings shows that one-third of LEED certified buildings consume more energy than conventional buildings (Newsham et al., 2009). LEED is consensus-based and does not provide a scientific calculation behind its pointing system (Fowler & Rauch, 2006).

2.2.1.2 BREEAM

BREEAM was developed by the Building Research Establishment (BRE) of the United Kingdom in 1990. More than 562,000 buildings have received BREEAM certification, making BREEAM the world's leading environmental assessment framework for buildings (BREEAM, 2017). BREEAM consists of nine assessment categories as shown in Figure 2-1. The score from each category is added up to calculate the overall score of the building and level of certification:

- 30% = Pass
- 45% = Good
- 55% = Very Good
- 70% = Excellent
- 85% = Outstanding

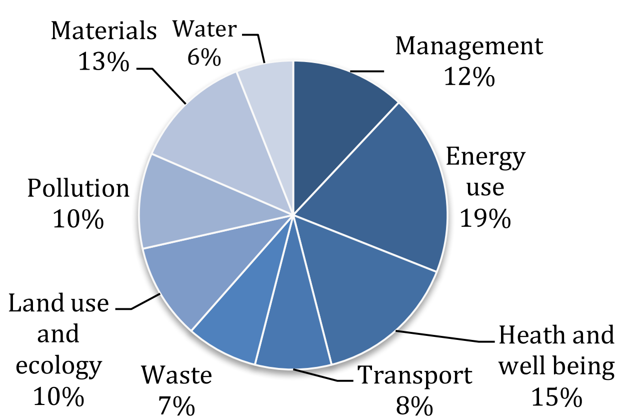

Figure 2-1 BREEAM categories

Similar to LEED, BREEAM is a point-based building rating system that is vulnerable to point hunting. BREEAM ignores the full life cycle impact of buildings and does not consider post-construction activities in its assessment.

2.2.2 Near Zero Building Assessment Framework

Passive House is the world leading rating system for assessment of NZEBs (Mihai et al., 2017). Passive House was developed in late 1990 in Germany and its main principle is using passive strategies to reduce energy demand in buildings. 'Passive design' is design that takes advantage of the surrounding climate to maintain a comfortable temperature range in the building (Australian Government, 2017).

Research shows that Passive House buildings have high thermal comfort and low energy consumption (Schnieders et al, 2006). The Canadian Passive House Institute (2017) noted that Passive House buildings have 80% to 90% energy performance savings compared to conventional Canadian construction. The following are the Passive House requirements (Schnieders et al., 2015):

- Annual space heat requirement of 15 kWh/(m2 year)
- Maximum total energy consumption for heating, hot water is 120 kWh/(m2 year)
- Maximum air leakage volume is 0.6 of the house volume per hour as measured at a pressure of 50 Pa.

Even though Passive House leads to better energy performance for buildings, the focus is only on the operational energy of buildings and embodied energy is not captured in the assessment. Building materials and water consumption are not part of the framework, making Passive House a one-dimensional energy-centric assessment framework.

2.2.3 Existing NZB Assessment Frameworks

Unlike for green buildings, there are few research and sustainability rating systems for NZBs (e.g., LBC), and they fail to adequately consider geography in defining NZBs. A net-zero building is a building system that uses sustainable materials and produces its needed energy and water throughout its life cycle. The LBC that was developed in 2006 is the world's leading assessment tool for NZBs. LBC comprised seven performance areas (petals): site, water, energy, health, materials, equity, and beauty, as shown in Figure 2-2. These are subdivided into a total of twenty Imperatives, each of which focuses on a specific sphere of influence (ILBI, 2012).

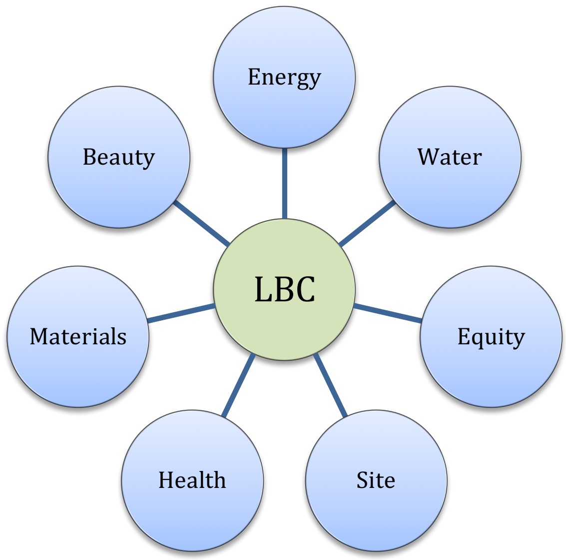

Figure 2-2 LBC petals

To receive LBC certification, a building must meet all imperatives assigned to a typology (i.e. renovation, building, landscape and infrastructure, or neighborhood). Also, LBC certification is based on actual rather than model performance of the building. These two points distinguish LBC from green building rating systems such as LEED or BREEAM.

The LBC was developed to raise the bar for green building assessment by targeting rigorous sustainability measures for green building design and construction. Two of these measures are net zero energy and net zero water. The net zero water target of LBC is that "one hundred percent of the project's water needs must be supplied by captured precipitation or other natural closed loop water systems that account for downstream ecosystem impacts, or by recycling used project water. Water must be appropriately purified without the use of chemicals." The net zero energy target of LBC is that "one hundred percent of the project's energy needs must be supplied by on-site renewable energy on a net annual basis" (ILBL, 2012).

Even though LBC has set a standard for NZBs, it has many limitations. First, LBC does not cover the full triangle of sustainability assessment (why net zero, what is net zero, and how to achieve net zero). LBC only defines a set of net zero and sustainability targets for buildings and points out the benefit of sustainability.

LBC does not assist users with how to achieve the defined targets. There is a need for a decision support tool that defines what a NZB is and evaluates sustainability options to achieve net zero targets. Moreover, LBC does not consider the full cradle-to-grave life cycle of buildings. Considering that buildings have a long life span and their end life (e.g., demolition, recycle, landfill) has a considerable environmental footprint, the full cradle-to-grave life cycle of NZBs should be considered.

LBC does not take the surrounding environment of a building fully into account and only defines a single target for all buildings. Considering that the building and construction industry is closely linked to geographical characteristics of location, there is a clear gap in spatial analysis in LBC. A building assessment tool should be able to provide a location-specific solution on how to achieve net zero targets in buildings. Also, it should consider the impact of buildings throughout their life cycle from cradle to grave.

Table 2-2 shows the sustainable building assessment frameworks, their main application, criteria of sustainability assessment, method of assessment, and pros and cons.

One of the main shortcomings of all building assessment tools is the lack of attention to local natural resources. Despite the fact that building performance is tied to its location, regional consideration is very limited in current sustainable building assessment systems. Sustainability impact assessment methodologies should include an appropriate level of regional consideration (Bare, 2014).

Regional considerations are only partially covered in current green building and net zero rating systems. For example, LEED only awards four points for projects targeting credits that are identified as regional priority credits, and two points for projects pursuing regional building materials. This is only 5% of the total number of LEED points. Also, the selection of regional credits for each region is questionable. For example, even though Alberta, Canada suffered from a drastic flood in 2013, LEED Canada does not identify stormwater management (LEED credits SS6.1 and SS6.2) as regional priority credits for Alberta, Canada. Eliasson (2000), Cidell and Beata (2009), Cidell (2009), and Hossaini et al. (2014a) have studied the connection between points earned by buildings following the major rating systems and building location. Results show that there is no clear connection between location of buildings and the points achieved. An example of regional assessment of LEED projects can be found in Appendix B (Hossaini et al., 2014a). Natural Capital Assessment can be used to study availability of local resources for buildings.

Table 2-2 Sustainable building assessment frameworks

Name	Focus	Method	E	W	M	LCA	LCC	R	D	Objective and Strength	Limitations
Legends	*E: Energy, W: Water, M: Materials, R: Regional Consideration, D: Decision Support*										
Energy Star	Green Building	Single Attribute, Pass Fail	X	X						Energy Star is developed by US EPA and Department of Energy (DOE) and focuses on energy in buildings. It uses benchmarking method to certify products that are energy efficient. It is a reliable system and widely used across North America.	The entire focus of Energy Star is on products that can contribute to energy and water efficiency in buildings. It does not evaluate the overall performance of green buildings and does not consider other aspects of buildings including building materials.
LEED	Green Building	Point-based, Simple Additive System	X	X	X					LEED is a popular green building rating system developed by USGBC. It is easy to use and covers different aspects of buildings including energy, water, indoor air quality, and building materials.	The point-based nature of the framework can lead to point hunting, where non-relevant points are targeted without addressing major issues such as energy conservation or water efficiency.
Built Green	Green Building	Point-based, Simple Additive System	X	X	X					Built Green is a third-party certification program for residential buildings. Similar to LEED it covers energy, water, indoor air quality, and building materials for sustainability assessment. Built Green is popular among single family homes in Canada because its certification cost is lower that other rating systems and involves less paperwork.	Built Green does not provide a decision support to its users. Sustainability criteria of this rating system are prescriptive, and verification and quality assurance are widely considered. Also, the entire scope focuses on residential buildings and building types such as commercial and institutional are not considered in the rating system.

Name	Focus	Method	E	W	M	LCA	LCC	R	D	Objective and Strength	Limitations
BREEAM	Green Building	Point-based, Weighed Additive System	X	X	X					BREEAM was developed by Building Research Establishment (BRE) of the United Kingdom. BREEAM is a weighted additive system where determination of weight mostly involves "judgmental or consensus-based". Expert opinions are used to rank the parameters and then weightings are allocated by analyzing data through various methods such as, analytic hierarchy process (Chew and Das, 2007).	BREEAM is a point-based building rating system that is vulnerable to point hunting. BREEAM ignore the full life cycle impact of buildings and does not consider post-construction activities in its assessment.
WELL	Green Building	Point-based, Simple Additive System			X					WELL standard is administrated by the International WELL Building Institute (IWBI) and measures attributes of buildings that impact occupant health. WELL considers seven main factors: Air, Water, Nourishment, Light, Fitness, Comfort, Mind.	Similar to LEED and BREEAM, WELL is a point-based system where point hunting can occur. WELL's main focus is on occupants' health and comfort, therefore energy conservation and water efficiency are not covered in this standard.
Passive House	Near Zero Energy Building	Single Attribute, Pass Fail	X							Passive House was developed in late 1990 in Germany and its main principle is using passive strategies to reduce energy demand in buildings. Passive House buildings have superior energy performance and lead to 80% to 90% energy savings compared to conventional buildings.	The focus of Passive House is only on the operational energy of buildings, and embodied energy is not captured in the assessment. Building materials and water consumption are not part of the framework, making Passive House a one-dimensional energy-centric assessment framework.

Name	Focus	Method	E	W	M	LCA	LCC	R	D	Objective and Strength	Limitations
LBC	Net Zero Building	Multi-Attribute, Pass Fail	X	X	X					The LBC developed by ILFI is the leading assessment tool for NZBs. LBC comprises seven performance areas (petals): site, water, energy, health, materials, equity, and beauty. To receive LBC, the building must demonstrate compliance in all categories.	LBC only defines a set of net zero and sustainability targets for buildings and points out the benefit of sustainability. LBC does not assist users with how to achieve the defined targets. LBC does not consider the full cradle-to-grave life cycle of buildings. LBC does not take the surrounding environment of a building fully into account and only defines a single target for all buildings.
Zero Energy Certification	Near Zero Energy Building	Single Attribute, Pass Fail	X							Zero Energy Certification is developed by ILFI for buildings that achieve only the net-zero energy performance of LBC.	Zero Energy Certificate is a single attribute, where the entire focus is on energy performance. Water and building materials are excluded from the assessment.
Proposed Framework	Net Zero Building	Multi-Attribute, Performance-based	X	X	X	X	X	X	X	The proposed framework aims to address limitations of the above rating systems and provide a multi-attribute performance-based framework for assessment of NZBs. It considers building's location to help building achieve the net zero targets. The framework covers the entire life cycle of the building	Refer to Section 6.4

2.3 Natural Capital Assessment

The term 'natural capital' was first used by the famous economist E.F. Schumacher in his book, *Small is Beautiful* (Schumacher, 1973). The concept has since been used by many ecologists, scientists, economists, and environmentalists. It was rapidly adopted for the sustainability community because it addresses environmental issues with economic thinking and decision-making (Arias-Maldonado, 2013).

Natural capital is the world's stock of natural resources, including sunlight, water, land, air, and renewable resources. In other words, it is all formations of the earth's biosphere that support the ecosystem and human activities. The utilization of natural capital over time allowed humans to create the built environment and develop infrastructures (Mellino et al., 2015). Costanza and Daly (1992) and Costanza et al. (1997) provided a detailed explanation of natural capital.

Natural capital can be altered by humans, but it cannot be created by humans. Humans can only facilitate restoration of natural capital (Collados & Duane, 1999). Therefore, it is necessary to preserve the natural capital in a sustainable manner. A sustainable manner means using natural resources to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Natural capital should follow the impact mitigation hierarchy: avoidance, minimization, restoration, and offset (Houdet et al., 2016). Table 2-3 summarizes the recent studies that used natural capital for sustainability assessments in the literature.

These studies can be categorized into two groups. The first group focuses on assessment of natural capital for sustainability and economic development at a global and macro level. These studies often develop natural capital-based models to study sustainability of global economy. Collados and Duane (1999) developed a model for the relationship between natural capital and quality of life to evaluate sustainable development. This study evaluated more than 50 regional development paths and identified six paths that lead to sustainable development with economic growth.

Table 2-3 Recent literature summary for natural capital assessment

Reference	Natural capital	Sustainability	Economic Development	Built Environment	Urban Planning
Collados and Duane (1999)	X	X	X		
Geldrop and Withagen (2000)	X	X			
Comolli (2006)	X	X	X		
Bastianoni et al. (2007)	X	X		X	
Blignaut et al. (2014)	X	X			
Peng et al. (2015)	X	X	X	X	X
Kemkes (2015)	X	X	X		X
Hackett and Moxnes (2015)	X	X			
Pelenc and Ballet (2015)	X	X	X		
Mellino et al. (2015)	X	X	X	X	X
Houdet et al. (2016)	X	X	X	X	X
Ding and Banihashemi (2017)	X	X		X	X
Note: NZBs are not addressed directly in the recent literature summary.					

Geldrop and Withagen (2000) developed a model for optimal use of natural capital in a utilitarian framework to study sustainable development. The authors concluded that natural capital reaches an equilibrium state if sustainably managed. Comolli (2006) created a model to study the importance of substitutability of man-made (or manufactured) capital for natural capital (renewable and nonrenewable resources) in the production of goods and services in the economy. Blignaut et al. (2014) identified three key strategies for transition toward sustainability, namely appropriate sustainable technologies, revising behaviour consumption patterns, and investment in the restoration of natural capital (RNC); they selected RNC as the most important factor and called it the 'game changer.' Other studies that fall into this group include Hackett and Moxnes (2015), and Pelenc and Ballet (2015).

The second group focuses on natural capital at a micro (regional) level and its application for sustainability of built environment and urban planning. Some studies in this group developed a model for urban planning of regions or cities. For example, Peng et al. (2015) developed a multidimensional 'ecology-equity-efficiency' framework to quantify the sustainability of natural capital utilization in Beijing City, China. Kemkes (2015) evaluated the role of natural capital in sustainability of Upper Svaneti region in Georgia. Mellino et al. (2015) evaluated natural and human capital for the Campania region in Italy. Ding and Banihashemi (2017) reviewed the ecological and carbon footprints for improving sustainability of cities.

There is only a limited number of studies that focused on the building and construction industry. Bastianoni et al. (2007) developed a methodology for assessment of natural capital in building construction in Italy. That study also focuses on how to reduce the natural capital appropriation of building construction by using renewable energy resources and 'environmentally inexpensive' materials. However, the study does not consider the entire life span of building construction and focuses on the construction phase only. Other studies that focus on NZBs or near-zero buildings mainly focus on energy as the main component of natural capital. Wells et al. (2018) reviewed the future of net zero energy buildings in the Australian context, and Attia et al. (2017) focused on future challenges on near-zero energy buildings in Southern Europe.

There is a clear gap in the literature regarding use of natural capital in assessing buildings' potential to move toward net zero targets (Ding & Banihashemi, 2017). The idea presented in this thesis focuses on assessing natural capital to achieve net zero targets in buildings. The entire life cycle of buildings is considered in the assessment. Natural capital can be strategically used in buildings to reduce their environmental footprint and help them be more sustainable. If carefully planned and managed, 'natural capital' is enough for buildings to become self-sufficient and have a net zero impact on the environment. Natural capital is a broad concept with many dimensions, and as such it is beyond the scope of this thesis to address all the components of natural capital. The objective of this research study is to focus on the most important components of natural capital as it relates to building and construction. Therefore, only the top three elements of water, energy, and building materials have been selected.

2.4 Main Drivers of Sustainable Buildings and Sustainable Building Policies

In this section, the main drivers of sustainable buildings around the world are discussed and a critical review is conducted for the current sustainable building policies and regulations in the province of BC.

2.4.1 Main Drivers of Sustainable Buildings Around the World

There are various motivations for moving toward green building practices. Darko et al. (2017) performed a comprehensive review of drivers of sustainable buildings by reviewing 42 recent publications on green buildings (since 2006). Authors identified a total of 64 drivers for sustainable construction and noted that the most important driver is 'government regulations and policies,' ahead of energy conservation, reduced life cycle costs, and environmental protection. Government regulations and policies create a clear direction for sustainability targets in regions and provide a fair environment for all stakeholders in the construction sector. These policies and regulations have proven to be effective in leading change and raising awareness in the building sector (Arif et al., 2012).

In recent years, many governments around the world have moved toward sustainable building policies and provided incentives for the green building market (Wang et al., 2014). Scandinavian countries were among the first to introduce green building regulations and energy efficiency policies (Alouhi et al., 2015). To reduce energy dependency (Perez-Lombard et al., 2011), the European Union (EU) established the

‘Nearly Zero Energy Building’ directive for all new buildings by 2020 (EPBD, 2010). In Asia, the Chinese government initiated a green building policy in the 1980s (Ye et al., 2013). Other Asian countries such as India, Hong Kong, and Singapore have implemented similar policies for sustainable buildings (Gou & Lau, 2014). In North America, the United States has passed an Act to support the goal of net zero energy for all new commercial buildings by 2030 (EIA, 2006). In Canada, the government goal is to develop and adopt a “net zero energy ready” model building code by 2030 (Government of Canada, 2017). To develop such a building code, the Canadian provinces and territories need to develop a new policy framework for NZBs that considers a fair distribution of costs and benefits for each stakeholder.

2.4.2 Current Sustainable Building Policies and Regulations in BC

Current sustainable building policies and regulations in British Columbia can be categorized into provincial regulations and city by-laws or policies.

2.4.2.1 Provincial Regulations

Construction in BC needs to follow the BC Building Code, which includes requirements for the minimum energy efficiency of buildings and their equipment (Government of British Columbia, 2017a). Buildings have the option to follow either of the following two energy standards: the National Energy Code for Buildings or the American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE 90.1.

In 2016, the Government of BC released the BC Energy Step Code, a voluntary roadmap that establishes energy performance targets for new buildings. It is a voluntary tool that local governments across the province can use to encourage construction of more energy efficient buildings, as compared to the minimum energy performance of the building code. The objective of the BC Energy Step Code is to establish a guide for transition to net zero energy ready buildings by 2032 (Government of British Columbia, 2016). The BC Energy Step Code is not mandatory and at the time of the article, none of the local governments in BC had adopted this roadmap as a regulation or by-law requirement for construction.

2.4.2.2 Local Government By-laws and Regulations

Sustainable building policies of the top cities in British Columbia with highest population are shown in Table 2-4.

The data from Table 2-4 shows that none of the local governments have a mandate for all new building constructions to incorporate sustainability measures. At most, they require targeting LEED or other equivalent green building rating systems for buildings that apply for rezoning. Rezoning is the process of changing the land use from its original use definition. The City of Vancouver has the toughest requirements among the local governments in BC and requires all projects that go through rezoning to meet the requirements of low emission or near zero emission green building. Other cities do not have a strong regulation for private developments and mostly provide roadmaps, guidelines, or a set of sustainability recommendations. Public buildings are required by most cities to implement requirements of third party green building rating systems or equivalent measures.

Considering that building construction in BC has steadily been increasing since the financial crisis in 2009 (Government of British Columbia, 2017b), the province lacks a unified and comprehensive sustainable building policy to combat the environmental impacts of building construction activities. Government regulations and policies are the most important catalyst for sustainable construction development (Darko et al., 2017). The policy framework discussed in this thesis considers the rich natural capital stock of the province and suggests a fair cost and benefit distribution of implementing new net zero targets in buildings.

Table 2-4. Local government green building policy and regulations

Jurisdiction	P	M	Coverage	Policy, Regulation, Guideline or Recommendation
Legends	*P: Population (Statistics Canada, 2016), M: Mandatory?*			
City of Vancouver (2017b)	631,486	Yes	Building rezoning only	- LEED Gold certification and energy performance limits (low emission) or Passive House certification (near zero)
City of Surrey (2017)	517,887	No		Voluntary recommendation to follow LEED
City of Burnaby (2017)	232,755	No		LEED or LEED equivalency measures are sometimes requested as part of Rezoning
City of Richmond (2017)	198,309	Yes	Industrial and office buildings in certain areas	LEED Silver or LEED Silver equivalency
City of Abbotsford (2017)	141,397	No		Voluntary recommendation for energy, water and waste management
City of Coquitlam (2017)	139,284	No		Voluntary recommendation for LEED, Built Green and other rating systems
City of North Vancouver (2017)	138,833	Yes	Public buildings and some rezoning applications	LEED or Built Green certification or equivalency
City of Kelowna (2017)	127,380	Yes	Public buildings and some rezoning applications	LEED certification
City of Victoria (2017)	85,792	Yes	Public buildings and some rezoning applications	LEED Silver certification

2.5 Uncertainty Analysis for NZB

First, a brief background on uncertainty analysis and a review of current literature is provided in this section. Then, sources of uncertainty in building rating systems are identified and their impacts are studied.

2.5.1 Uncertainty Analysis

The main objective of uncertainty analysis can be described as finding uncertainties in input and output of a system (Lomas & Eppel, 1992). There are many advantages for uncertainty analysis; Hopfe and Hensen (2011) identified the following benefits:

- It can lead to the simplification of a model by parameter screening (De Wit, 1997)
- It can examine the robustness of a model (Litko, 2005)
- It is a measure of quality assurance of a model (Hopfe et al., 2006)
- It can provide decision support by showing the effect of the parameters on the outcome of a model (what-if analysis) (Gokhale, 2009).

Generally there are four methods to address uncertainty (Heijungs & Huijbregts, 2004):

- The scientific approach focuses on design of experiments and conducting more research.
- The group discussion approach relies on experts' judgments and professional opinions.
- The official approach uses values developed by authoritative institutions such as ISO.
- The statistical approach uses numerical and probabilistic methods.

The first three methods aim to reduce uncertainty, while the last approach's goal (statistical approach) is to investigate the impact of uncertainty on the outcome (Heijungs & Huijbregts, 2004). The first step in addressing uncertainty is finding the origin of uncertainties and estimating them. Then, the impacts of uncertainties on the outputs need to be evaluated. The final step is explaining and presenting the results and using the results to manage uncertainty (Soltani, 2015).

Sreeraj et al. (2010), Zhou et al. (2013), Lujano-Rojas et al. (2012), and Lu et al. (2017) studied uncertainty of renewable energy systems. The focus of these studies is developing methods based on a probabilistic approach to assist in sizing, load analysis, and design of renewable energy systems. Lu et al. (2017) provided an in-depth review of uncertainty analysis of renewable energy systems design.

When it comes to analysis of sustainable building assessment, there are not enough studies that consider uncertainty analysis. As noted by Hong et al. (2016), uncertainty analysis is a useful technique in determining if the results of LCA are sufficiently reliable when making decisions. However, only a few studies in the literature have considered the critical factors during the building construction phase to calculate carbon emissions. Building rating systems are incapable of dealing with uncertainties associated with data limitations and expert opinions, which effects reliable sustainability assessment (Umer et al., 2016). Umer et al. (2016), Shiau et al. (2015), Alsulami and Mohamed (2014), Yoe et al. (2010), Gasparatos et al. (2009), Hunt et al. (2008), and Boschmann and Kwan (2008) have found that the existing sustainability assessment tools cannot handle uncertainties in indicator values and benchmarks due to data limitations and expert opinions.

2.5.2 Sources of Uncertainty

Uncertainty can arise from various sources. Generally, the sources of uncertainty are classified as parameter, model, and scenario (Lloyd & Ries, 2007). Parameter uncertainty is caused by errors or negligence in the values of input data. Parameter uncertainty happens when measurements of input data are unavailable, imprecise, unreliable, or biased (Lloyd & Ries, 2007). Model uncertainty deals with inaccurate predictions due to the lack of suitable scientific hypotheses (USEPA, 2013). Scenario uncertainty refers to the ambiguity in using one scenario over another (Walker et al., 2003), such as assuming that building materials will be sent to landfill (selected scenario), while the materials could be recycled or reused (other possible scenarios). Table 2-5 lists the main sources of uncertainty in NZB assessment.

Table 2-5 Sources of uncertainty in sustainable building rating systems

Type of Uncertainty	Source of Uncertainty
Parameter	• Energy system parameters • Water system parameters • Natural capital parameters
Model	• Uncertainties of Life Cycle Assessment (LCA) • Uncertainties of Life Cycle Cost (LCC) analysis • Uncertainties of Natural Capital Assessment (NCA)
Scenario	• End-of-life use of building materials • Climate change • Geopolitical uncertainty

2.6 Summary

The objective of this chapter was to provide a background on the main components of this thesis, including sustainable buildings, sustainable building assessment frameworks, natural capital, and main drivers of sustainable buildings. This review shows that there is a knowledge gap for a comprehensive NZB assessment framework that uses local natural capital to assist building stakeholders achieve net zero targets in the building. The developed framework discussed in the next chapter considers the life cycle impacts of buildings, regional characteristics, and available natural capital to provide location-specific solutions to achieve net zero targets in buildings.

Chapter 3. Research Methodology

3.1 Introduction

As noted in Chapter 2, the literature review shows that there is a knowledge gap regarding a comprehensive NZB assessment framework that covers all the main components of NZBs. The assessment framework should cover the full life cycle impact of buildings from cradle to grave. The assessment framework should be capable of analyzing local natural resources available at the building's location and provide decision support to achieve net zero targets.

The methodology presented in this chapter aims to fill this research gap. In this framework, natural capital assessment complements net zero water assessment, net zero energy assessment, LCA, and LCC to create a model for sustainability assessment of NZBs over their life cycle. This framework aims to assist building stakeholders in the pre-design stage to evaluate sustainability options for implementation in the building's design.

Figure 3-1 shows the high-level methodology flowchart for this research. The framework consists of four main steps. At the first step, a system boundary for the building is defined and related building data that are required in the framework are collected. Then, a demand assessment is performed for each of the main components of the building. Energy demand, water demand, and building materials demand are calculated. At the next step, the building location is analyzed and natural capital assessment is conducted for three modules: energy system, water system, and building materials. Outputs of these steps are fed to the system's integration module to identify the building's environmental footprint. A decision support tool is then used to identify how the building can become net zero carbon over its life cycle. Finally, an economic assessment is performed to evaluate the cost-effectiveness of the building.

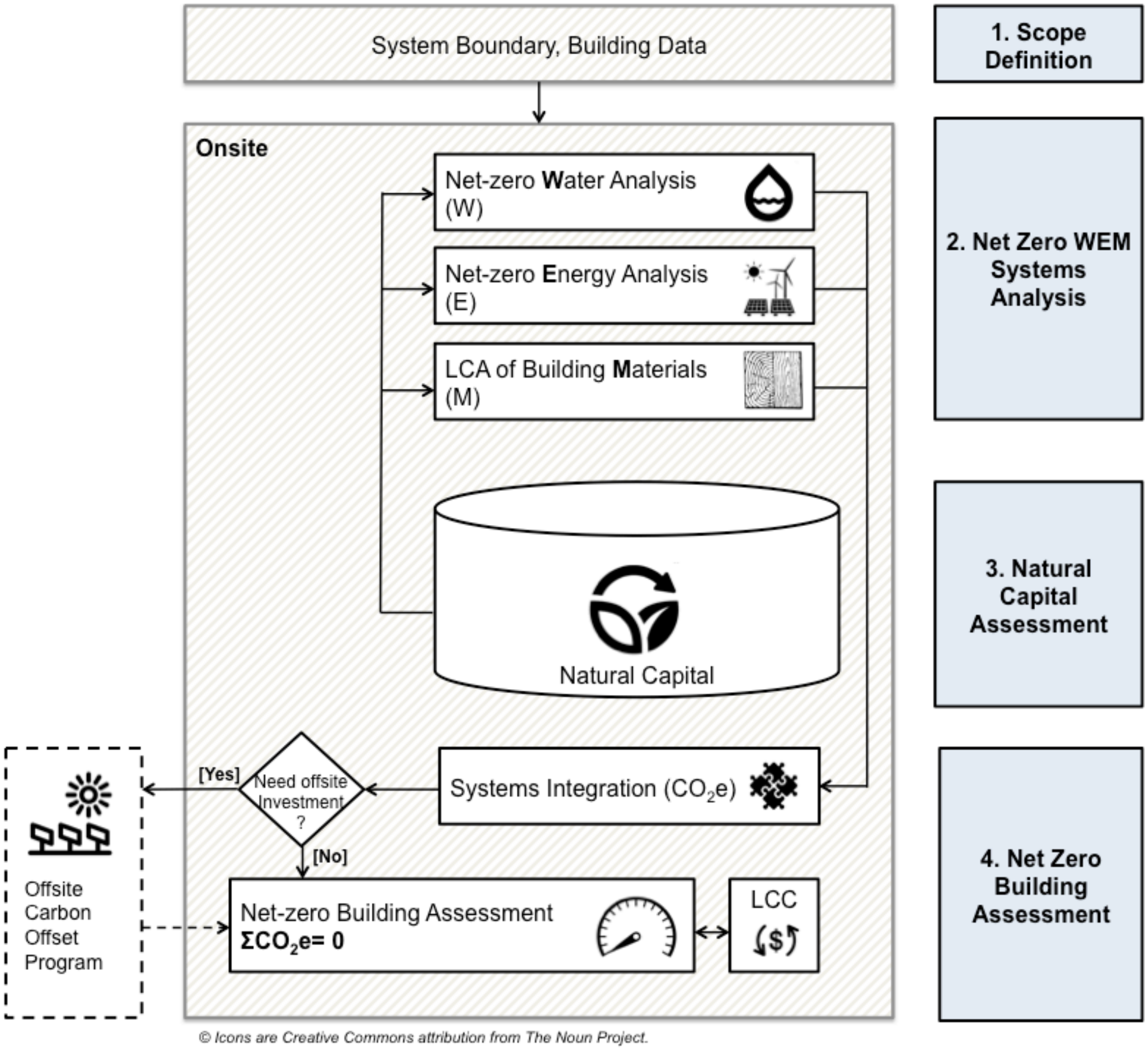

Figure 3-1 Methodology flowchart

3.2 Scope Definition

The first step of this framework is to identify the scope and define the system boundary. Similar to the LCA framework, the NZB assessment framework starts with a clear identification of the goal and scope of the study, system boundaries, and the data needed in the framework.

The goal of this framework is to assess sustainability of NZBs and provide a decision support on how the building can achieve the net zero targets using local natural resources. Notable scholars including Chwieduk (2013) and Anink et al. (1998) emphasized that in sustainable building assessment, stress is put on the three most important flows through a building: energy, water, and building materials. Therefore these three building systems are considered for the assessment. The building and the land used directly to support the building's function (such as parking lot, outdoor green area) are considered as the building boundary.

3.2.1 Building Data

Table 3-1 shows the list of building data that is required for this framework. Note that if the actual data is not available at the time of assessment, assumptions can be made based on other similar buildings.

Table 3-1 Building data

Name of the Building	Building Roof Area (m^2)
Location of the Building	Building Life Span (years)
Building Use Type (Institutional, Residential, Commercial, Office)	Cost of local energy (\$/kWh) and local water (\$/m^3)
Total Floor Area (m^2)	Annual Operating Hours (hr)
Total Site Area (m^2)	Number of Full Time Occupants
Building Footprint (m^2)	Number of Transients

Data related to climate and environment of the region where the building is located need to be collected. The required regional data related to each building system is discussed in the following sections. In addition to the regional data, a cluster of sustainable building technologies, systems, and materials that can help the building achieve net zero targets are collected. Table 3-2 shows the data related to each building system. These data are evaluated based on their applicability, efficiency, and availability for each region. For example, photovoltaic (PV) systems are evaluated based on the photovoltaic potential for solar energy use across the region of study. These data will be discussed in detail in the following sections.

Table 3-2 Sustainable building systems

Sustainable Building Components	Items
Net zero energy	On-site renewable energy systems
Net zero water	Closed loop water systems, low flow water fixtures
Sustainable building materials	Major building materials and alternative sustainable materials

Figure 3-2 shows a snapshot of the developed framework for building data.

General Project Information

Name	Okenagan College - Centre Of Excellence	
Location	583 Duncan Ave W, Penticton, BC V2A 8E1	
Building Type	Institutional	
Floor Area	7335	m2
Site area	44100	m2
Building footprint	4680	m2
Building roof area	5455	m2
Number of full time occupants	50	FTE
Number of transients	200	FTE
Building Life Span	60	Years

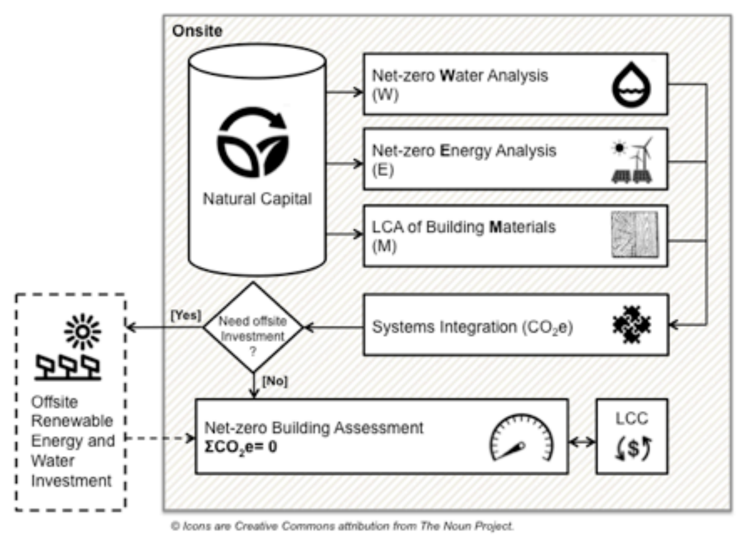

Figure 3-2 Snapshot of the developed framework – building data

3.3 Net Zero Energy Analysis

As noted in the literature review, the main concept that comes to mind when discussing NZBs is ‘energy.’ Berggren et al. (2013), Zeiler and Boxem (2013), Thomas and Duffy (2013), Dang et al. (2014), Giordano et al. (2015), and Sorensen et al. (2017) have only considered energy as the main component of NZBs. There is no standard definition for ‘zero’ calculating methodology (Marszala et al., 2011). The general energy equilibrium equation for buildings can be defined as:

$$\mathbf{E}_{\text{demand}} = \mathbf{E}_{\text{supply}} - \mathbf{E}_{\text{losses}} \qquad \textbf{\textit{[Eq. 3-1]}}$$

where $\mathbf{E}$ is energy.

The net zero energy analysis of the proposed methodology is based on [Eq. 3-1]. Assuming that buildings will have an energy storage system to cover peak demand and $\mathbf{E}_{\text{losses}}$ are negligible, to have a self-sufficient and net zero energy building, $\mathbf{E}_{\text{supply}}$ should be equal to $\mathbf{E}_{\text{demand}}$. E_{demand} of the building is discussed in section 3.3.2. The $\mathbf{E}_{\text{supply}}$ parameter is discussed in section 3.3.3. $\mathbf{E}_{\text{losses}}$ occur in the energy systems mainly when one form of energy is converted to another form. To account for these losses, system efficiency (%) is considered in the energy equation and described in Table 3-3.

All buildings need to consume energy to function properly, so to achieve a net zero energy objective, buildings should be designed to consume less energy (via efficient design and systems) and offset that energy use by generating renewable energy. Four parameters should be considered in [Eq. 3-1].

3.3.1 Period of Assessment

Period of assessment refers to a timeframe in which Eq. 3-1 is applied. There are different timeframes used in the literature for the energy assessment of buildings, including annual energy consumption and generation (Mertz et al., 2007), operation phase of the building (use phase) (Zeiler & Boxem, 2013; Thomas & Duffy, 2013), or complete life cycle of the building (Hernandez & Kenny, 2010; Goggins et al., 2016). A main drawback of the existing net zero assessment frameworks in the literature is that the cradle-to-grave life cycle of the building is not considered in the assessment. Jin et al. (2014) emphasized that to achieve a true net zero energy building, a life cycle analysis should be set up to assess the whole energy performance.

Therefore, in the proposed framework energy use from all life cycle stages of the building is considered, including construction, operation, and the End-of-Life (EOL) phase. EOL refers to the demolition and deconstruction phase of the building. The Eq. 3-1 can be rewritten as:

$$E = \sum_{t=0\ (cradle)}^{t=T\ (grave)} E_{Construction} + E_{Operation} + E_{EOL} \qquad \textbf{\textit{[Eq. 3-2]}}$$

3.3.2 Building Energy Demand

The building energy systems can be sub-divided into the process and non-process systems. Process energy refers to energy used by equipment and appliances in a building, such as TV, refrigerator, and dishwasher. The non-process (also referred to as regulated) energy refers to the energy demand of the core building systems. The non-process energy systems include the following:

- Lighting system (E_L) provides lighting within the building boundary
- Space Heating and Cooling (E_{HC}) system supplies thermal energy in the building for occupant comfort
- Pumps (E_P) distribute the water within the building boundary
- Fans (E_F) distribute the air for ventilation
- Service Water Heating (E_{SWH}) is used to condition the water supplied from pumps for interior use such as kitchen and toilets.
- Elevator (E_{EL}).

To calculate the building energy demand, design parameters shown in Table 3-3 are required.

Table 3-3 Building energy demand parameters

Phase	Energy System	Parameter	Unit of Measurement
Construction		Average energy consumption for the construction phase	Gj/m2
Operation	Envelope	Average window-to-wall-area ratio	%
		Overall window USI-value	$W/m^2°C$
		Window shading coefficient	
		Overall wall RSI-value	$m^2°C/W$
		Gross exterior wall area	m^2
		Overall roof RSI-value	$m^2°C/W$
		Gross exterior roof area	m2
	Heating, Ventilation, Cooling,	Heating efficiency	%
		Minimum outside air	$l/s/m^2$
		Percent of outside air controlled by DCV	%
		Percent of floor area cooled	%
		Cooling efficiency	COP
		Outdoor air economizer?	Y/N
		Efficiency of exhaust air heat recovery	%
		Service water heating fuel type (Electrical, Hydronic, Natural Gas)	
		Service water heating efficiency	%
	Lighting	Average lighting density - residential	W/m2
		Average lighting density - parkade	
		Parkade floor area	m2
		% of lighting load with occupancy sensor control:	%
	Process Load	Average process load density	W/m2
EOL		Average energy consumption for the EOL phase	Gj/m2

Since building energy systems are complex and integrated, energy demand analysis needs to be done using computer-based Building Energy Modeling (BEM). BEM is physics-based computer simulation of building energy use based on building parameters. A BEM software uses these inputs to solve physics equations and calculate building energy use (US Department of Energy, 2017). Figure 3-3 shows the snapshot of the developed framework for energy demand analysis.

Energy Use Analysis

Construction		Average energy consumption construction phase		Gj/m2
Operation	Envelop	Average window-to-wall-area ratio:		%
		Overall window USI-value:		W/m²°C
		Window shading coefficient:		
		Overall wall RSI-value:		m²°C/W
		Gross exterior wall area:		m²
		Roof type:		
		Overall roof RSI-value:		m²°C/W
		Gross exterior roof area:		m2
	Mechanical (HVAC) System	Heating efficiency:		%
		Minimum outside air:		l/s/m²
		Demand control ventilation (DCV) type:		
		Percent of outside air controlled by DCV:		%
		Percent of floor area cooled:		%
		Cooling efficiency:		COP
		Outdoor air economizer?		
		Efficiency of exhaust air heat recovery:		%
		Service water heating fuel type:		
		Service water heating efficiency:		%
		Service water savings:		%
	Lighting	Average lighting density - residential		W/m2
		Lighting control - residential		% of floor area
		Average lighting density - parkade		
		Parkade floor area		m2
		% of lighting load with occupancy sensor control:		%
	Process Load	Average process load density		W/m2
		Percent served by electricity:		%
Demolition		Average energy consumption for the demolition		Gj/m2

Source of energy sypply in the region	HydroElectric
Primary Heating System	Electric

Figure 3-3 Snapshot of the developed framework – energy demand analysis

There are many standards for building energy systems; ASHRAE 90.1 (Ashrae, 2015) is the most widely used standard in North America. Government-developed computer simulation software can be used for energy modeling, including EE4 (Natural Resources

Canada, 2014) and eQuest (US Department of Energy, 2015). Also, there are other relatively simple energy modeling tools to provide quick estimates of energy performance of a building, such as Screening Tool for New Buildings (EnerSys Analytics, 2013).

3.3.3 Building Energy Supply

The energy demand of buildings can be supplied from off-site or on-site sources. The equation 3-1 can be rewritten as:

$$\mathbf{E}_{\text{demand}} = \mathbf{E}_{\text{supply on-site}} + \mathbf{E}_{\text{supply off-site}} - \mathbf{E}_{\text{losses}} \qquad \textbf{\textit{[Eq. 3-3]}}$$

Off-site refers to the energy sources that are located outside of the building boundary. Most conventional buildings are located in developed areas and can connect to the electric grid as the main energy supply source. The off-site grid energy can be from renewable or non-renewable energy sources. The energy can also be generated within the building boundary from renewable energy sources. The main renewable energy sources that are available to buildings are solar, wind, and geothermal energy. To achieve net zero, a building should generate renewable energy to offset the energy it uses over its lifetime within the building boundary (on-site). Natural capital assessment (discussed in Section 3.6) evaluates the renewable energies that are available at the building's location, and the building's capacity to generate renewable energies. Figure 3-4 shows possible energy supply options for buildings.

Buildings may have limited space to generate renewable energy or have excessive energy demand, hence might not be capable of generating their entire energy demand on-site. In this framework, an off-site renewable energy investment mechanism is provided to overcome this issue (discussed in Section 3.7). Figure 3-5 shows the energy demand results of the developed framework.

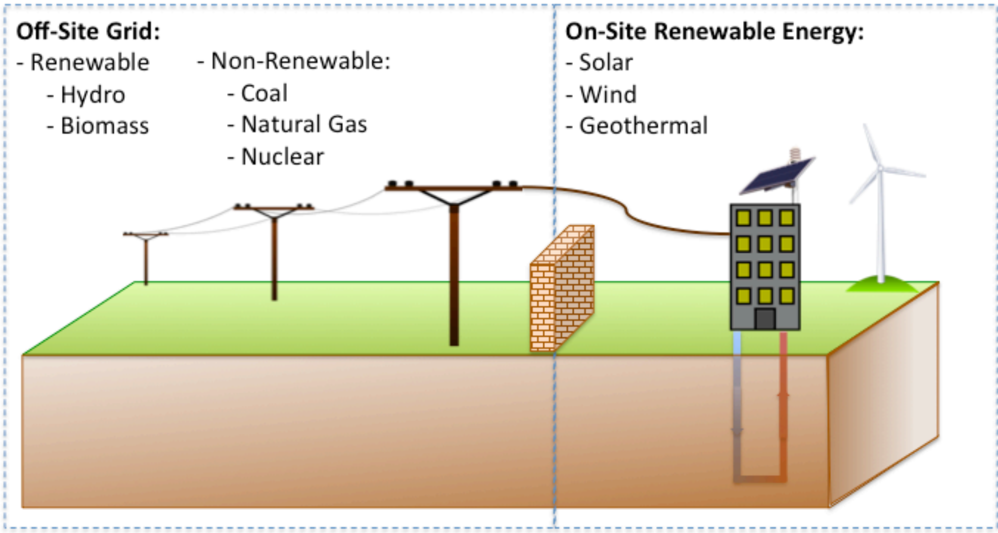

Figure 3-4 Energy supply options for buildings

Energy Use Results

Regulated energy	Energy Type	MJ
Lighting	Electric	554,128
Space heating	Electric	895,377
Space cooling	Electric	0
Pumps	Electric	70,915
Fans	Electric	176,385
Service Water Heating	Electric	22,079
Plug Loads	Electric	645,499

Operation Energy	Energy Supply	MJ	kwh	Average Emission Intensity (kg CO2/kwh)	Emission (kg CO2e)
	HydroElectric	**2,364,383**	656773.6	0.026	17076
	Natural Gas	**0**	0.0	0.5	0
	Oil/Other fuels	**0**	0.0	0.735	0
	Biomass	**0**	0.0	0.045	0
	Wind	**0**	0.0	0.026	0
	Nuclear	**0**	0.0	0.028	0
	Coal	**0**	0.0	0.888	0

Figure 3-5 Snapshot of the developed framework – energy demand results

3.3.4 Measurement Metrics

The energy demand and supply of the building is usually represented in 'Joules (J)'. Joules is the unit of measure for energy 'output'. Using Joules to represent energy for the sustainability assessment of buildings is not an effective metric since it does not capture the sustainability 'input' of the energy generation source. Energy represented in Joules neglects the environmental-friendliness of the energy generation source. For example, 1000 J of energy generated from a coal-fired power plant is treated the same as 1000 J of energy generated from a solar PV, which is a more sustainable solution with less environmental impact. To rectify this issue, the energy in Eq. 3-1 can be represented in terms of CO_2 equivalent used for the energy generation (CO_2e). CO_2e is an impact-based metric that can represent sustainability of net zero energy buildings. Conversion factors (CF) are used to show the carbon intensity of each energy source. The energy balance equation of the NZB framework can be shown as the following:

$$\sum_{t=0}^{t=n} E_{CO2} = \begin{bmatrix} E_{on-CS1} & E_{on-OS1} & E_{on-ES1} \\ \vdots & \vdots & \vdots \\ E_{on-CSm} & E_{on-OSm} & E_{on-ESm} \end{bmatrix} \begin{bmatrix} CF_1 \\ \vdots \\ CF_m \end{bmatrix} + \begin{bmatrix} E_{off-CS1} & E_{off-OS1} & E_{off-ES1} \\ \vdots & \vdots & \vdots \\ E_{off-CSm} & E_{off-OSm} & E_{off-ESm} \end{bmatrix} \begin{bmatrix} CF_1 \\ \vdots \\ CF_m \end{bmatrix}$$

Onsite energy supply during construction phase

[Eq. 3-4]

where,

t is time

n is building life span (years)

CF_1 is conversion factor for carbon intensity of energy source 1 (CO_2e/J)

E_{CO2} is energy in terms of CO_2e.

$E_{on\text{-}CS1}$ is the on-site energy supply during construction from the source 1 (J)

$E_{on\text{-}CSm}$ is the on-site energy supply during construction from source m (J)

$E_{on\text{-}OS}$ is the on-site energy supply during building operation phase (J)

$E_{off\text{-}ES}$ is the off-site energy supply during building end-of-life phase (J)

In Equation 3.4, CF is conversion factor for carbon intensity of an energy source. Emission factors are expressed in kilograms (kg) or metric tonnes (t) of GHG emissions per unit of energy consumption activity (J). A conversion factor shows the carbon intensity of a unit energy generated from a particular source (Government of British Columbia, 2016). CFs are calculated and issued by government agencies that are responsible for environmental protection. Table 3-4 shows the emission factors of main energy sources (WNA, 2018).

Table 3-4 Source of conversion factors

Energy Source	CF (kg CO_2e / GJ)
Solar PV	23
Natural Gas	139
Coal	247
Oil	204
Hydropower	8
Wind	7
Geothermal	34

Emission intensity of energy sources can change over time. With advancements in technology and science, the carbon intensity could be reduced. Also, if an energy source becomes scarce, carbon intensity of energy generation from that source could increase. Therefore, it is important to reevaluate and calculate the CFs throughout the project life cycle.

3.4 Net Zero Water Analysis

As noted in section 2.1, water conservation is not considered in a vast majority of NZBs in the literature. The NZB concept is closely tied to energy, and the importance of water is overlooked in the assessment frameworks. Water is an important and precious resource used in buildings. Water flow through the building boundary needs to be fully considered and analyzed for a true NZB (Chwieduk, 2013). This section discusses the water balance analysis for NZBs. Figure 3-6 shows typical domestic water use in buildings (Kloss, 2008). Showers, faucets, and toilets account for 60% of water use in buildings that can be easily monitored and reduced.

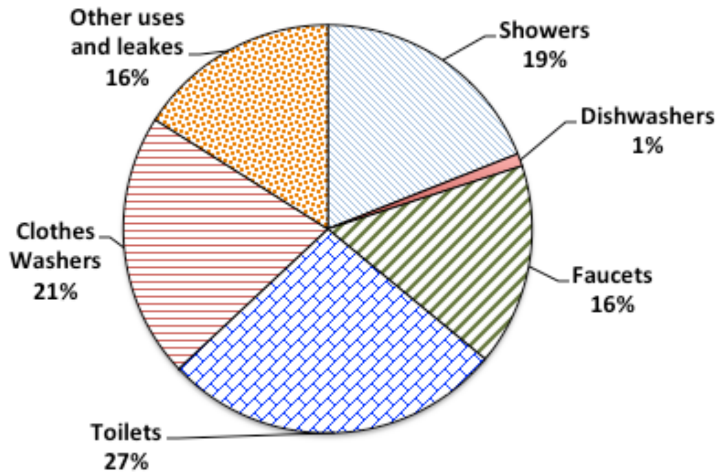

Figure 3-6 Domestic water use in buildings

3.4.1 Water Demand and Supply

The general water equilibrium equation for NZBs can be written as the following:

$$\mathbf{W}_{\text{demand}} = \mathbf{W}_{\text{supply on-site}} + \mathbf{W}_{\text{supply off-site}} - \mathbf{W}_{\text{losses}} \qquad \textbf{\textit{[Eq. 3-5]}}$$

where $\mathbf{W}$ is water.

Assuming $\mathbf{W}_{\text{losses}}$ are negligible, the water demand of the NZB is supplied from on-site or off-site resources. For a sustainable net zero state, the water captured by the building ($\mathbf{W}_{\text{supply on-site}}$) should be equal to water consumed by the building. Similar to an energy assessment, the life cycle approach is used for net zero water analysis in this framework. Figure 3-7 shows the water demand and supply of a typical NZB.

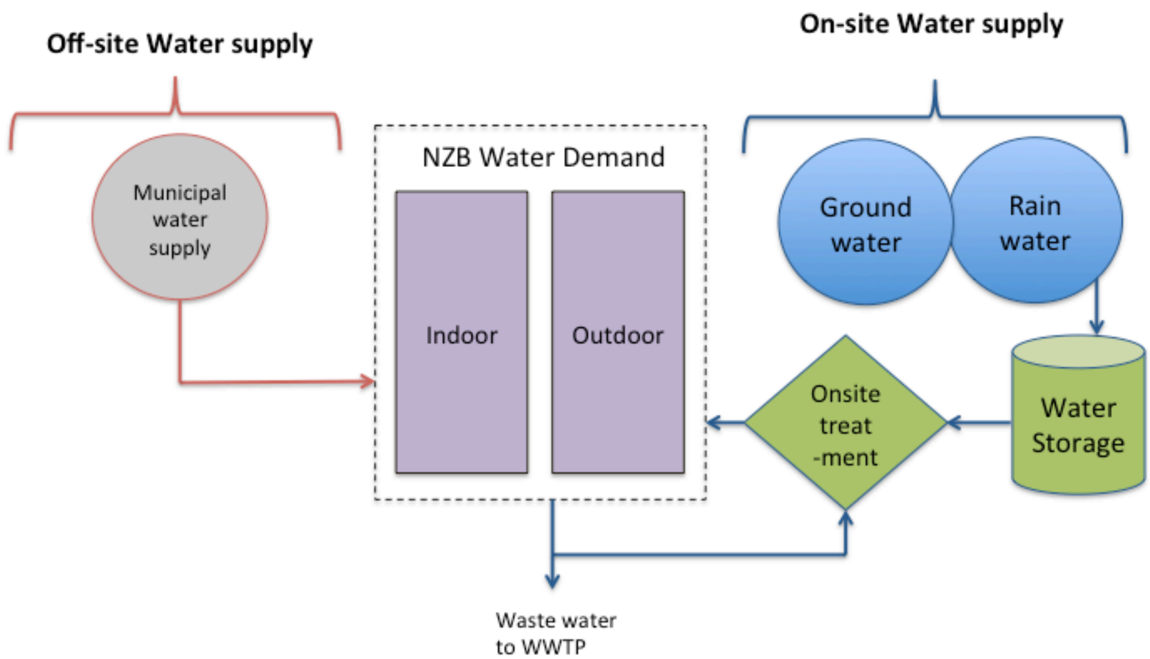

Figure 3-7 Water supply and demand of NZB

Water demand of NZBs can be sub-divided into indoor use and outdoor use. Indoor water use is defined as the water consumed by building occupants during operational phase of the building. This stream of water is used by:

- Flow fixtures such as kitchen faucet, lavatory faucet and showers.
- Flush fixtures such as washroom flushing

Water demand can be calculated using Equation 3-6 and 3-7:

$$\boldsymbol{Flow\ Fixtures} = Daily\ Use \times Use\ duration \times Flow\ rate \times\ FTE \times AWD \qquad \textbf{[Eq. 3-6]}$$

$$\boldsymbol{Flush\ Fixtures} = Daily\ Use \times Flow\ rate \times FTE \times AWD \qquad \textbf{[Eq. 3-7]}$$

where,

FTE = Number of full-time-equivalent building occupants

AWD = Annual working days

The outdoor water use is mainly for irrigation and some mechanical heating/cooling systems. The irrigation water use can be calculated using the following equation (CaGBC, 2016):

$$\boldsymbol{Irrigation\,water\,demand} = \frac{\boldsymbol{A \times ET_0 \times KL \times CE}}{\boldsymbol{IE}} \qquad \textit{\textbf{[Eq. 3-8]}}$$

where,

A is the irrigation area [m^2]

ET_0 is evapotranspiration rate for the region

KL is the landscape coefficient

CE is controller efficiency.

IE is irrigation efficiency

Table 3-4 shows the ET_0 major Canadian cities and Table 3-5 includes IE for main irrigation types (CaGBC, 2016).

Table 3-5 Evapotranspiration rate for selected Canadian cities (mm/month)

City	May	July	Sept
Victoria	91.5	121.3	55.3
Vancouver	97.5	128.4	60.0
Calgary	122.1	134.8	69.1
Edmonton	122.1	130.6	62.8
Toronto	101.6	138.2	71.6
Ottawa	109.0	133.8	66.5
Montreal	102.9	132.3	63.5
Quebec	100.3	125.1	59.0

Table 3-6 Irrigation efficiencies (IE)

Type	Efficiency
Sprinkler	0.625
Drip	0.90

Figure 3-8 shows the water analysis part of the developed framework.

Water Use Demand Analysis

Indoor Water Demand analysis

	Flush/Flow fixture	Daily use	Flow rate (LPF or LPM)	Use duration (sec)	Occupant users	Annual work days	Annual water use (L)
Flush Fixtures	High efficiency water closet	2	4.8	-	250	230	552000
	High efficiency urinal (male only)	1	1.9	-	125	230	54625
Flow Fixtures	Low flow shower	1	8.3	300	50	230	477250
	Low flow lavatory	3	1.9	12	250	230	65550
	Low flow shop sink	1	1.9	15	250	230	27312.5
	Low flow kitchen sink	20	6.8	15	5	230	39100
	Janitors sink	5	9.5	15	5	230	13656.25

Figure 3-8 Snapshot of the developed framework – net zero water analysis

To achieve the net zero goal, two main strategies are followed. The first strategy focuses on reduction of water demand (**W** $_{demand}$) by using indoor and outdoor water systems that require no or very low water (water impact avoidance/minimization). Examples of these systems include: no irrigation system, irrigation system with controller, low flow fixtures, low flush fixtures, and waterless urinals. The second step is to focus on sustainable on-site water supply strategies. Natural capital assessment (discussed in Section 3.6) is used to evaluate a building's potential to use groundwater resources and capture precipitation.

To show the environmental impact of the water supply source, water in NZB should be represented in CO_2e terms. Conversion factors (CF) are used to transform the carbon intensity of each water supply source. The water balance equation of the NZB framework can be shown as the following:

$W_{supply\ off\text{-}site}$ is the amount of CO_2e generated to supply an off-site water source to the building. This includes the CO_2e emission of water processing at the plant and transportation to the site. The CO_2e emission should be calculated using LCA as described in section 3.4.

$$\sum_{t=0}^{t=n} W_{CO2} = \begin{bmatrix} W_{on-CS1} & W_{on-OS1} & W_{on-ES1} \\ \vdots & \vdots & \vdots \\ W_{on-CSm} & W_{on-OSm} & W_{on-ESm} \end{bmatrix} \begin{bmatrix} CF_1 \\ \vdots \\ CF_m \end{bmatrix} + \begin{bmatrix} W_{off-CS1} & W_{off-OS1} & W_{off-ES1} \\ \vdots & \vdots & \vdots \\ W_{off-CSm} & W_{off-OSm} & W_{off-ESm} \end{bmatrix} \begin{bmatrix} CF_1 \\ \vdots \\ CF_m \end{bmatrix}$$

Off-site water supply (municipal water) during building operation

[Eq. 3-9]

where,

t is time

n is building life span (years)

W_{CO2} is water in terms of CO_2e.

$W_{on\text{-}CS1}$ is the on-site water supply during construction from the source 1 (L)

$W_{on\text{-}CSm}$ is the on-site water supply during construction from source m (L)

$W_{on\text{-}OS}$ is the on-site water supply during building operation phase (L)

$W_{off\text{-}ES}$ is the off-site water supply during building end-of-life phase (L)

CF_1 is conversion factor for carbon intensity of water-supply source 1 (CO_2e/L)

3.5 Building Materials

Materials are the fundamental component of buildings through their lifetime. In the context of NZB assessments, embodied carbon emission of building materials can account for a considerable environmental footprint, potentially higher than the environmental impact of energy and water systems. Yet, building materials are either inadequately considered or completely ignored from the scope of NZBs in the literature with reference to ILBI (2012), Berggren et al. (2013), Zeiler and Boxem (2013), Thomas and Duffy (2013), Jin et al. (2014), Dang et al. (2014), Pan (2014), Zhao and Pan (2015), Giordano et al. (2015), Goggins et al. (2016), Zhou et al. (2016), and Sorensen et al. (2017).

Building materials are considered in the NZB framework of this thesis. LCA is the most suitable method to study building materials for NZBs. LCA helps building stakeholders to understand the environmental impact and carbon footprint of various materials to select sustainable options. According to the ISO 14040 and 14044 standards (2006), LCA consists of four interactive stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Figure 3-9).

The first stage of LCA defines the system boundary and timeframe of analysis. The NZB building boundary is defined in Section 3.1. The timeframe of analysis includes cradle-to-grave stages of the building materials, including resource extraction, transportation, manufacturing, construction, operation and maintenance, and demolition/deconstruction.

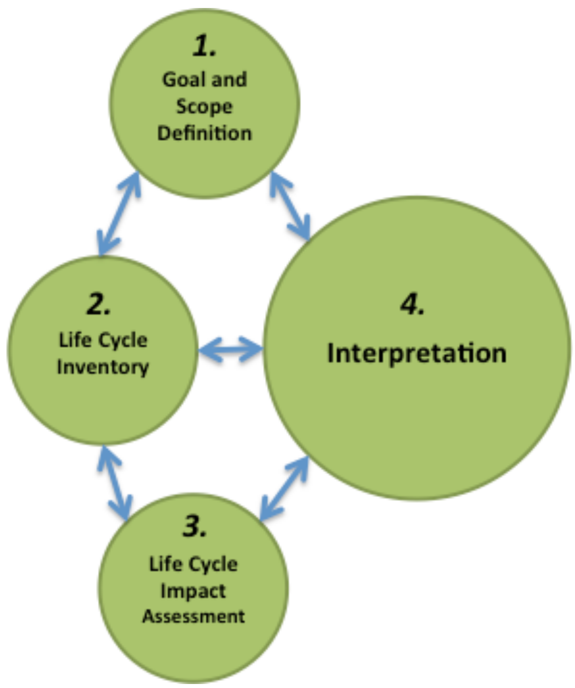

Figure 3-9 LCA stages (ISO, 2006)

At the Life Cycle Inventory (LCI) Analysis stage, inflows to the system are identified. Inflows include the building materials that are used for construction of the building. Quantity of building materials are calculated from one of the following sources:

- Building Information Model (BIM)
- Bill of quantities of materials
- Building design drawings

Once the building inflows are known, Life Cycle Impact Assessment (LCIA) is conducted. LCIA categorizes the life cycle inventory analysis results in terms of their significance and potential environmental impacts. The outcome of the calculation is a numerical indicator result typically stated on an equivalence basis, such as CO_2e. LCA is conducted according to the ISO 14040 standard to evaluate the carbon footprint of building materials ($\mathbf{M}_{CO2}$). LCA is also used to calculate the water footprint of building materials. The LCA can be conducted using various computer software tools such as Athena Impact Estimator (Athena Sustainable Material Institute, 2012) and SimaPro. Figure 3-10 shows the snapshot of the LCA step in the developed framework. Table 3-6 shows the demand and supply of NZB components.

Materials Use Analysis

Materials	Volume (m3)	Emission Intensity (CO2e/m3)	Emission (kg CO2e)	End of Life Scenario?
Concrete		210	0	Recycle
Glulam		147	0	Landfill
rebar		2111	0	Reuse
asphalt		493	0	
		Total:	**0**	

Figure 3-10 Snapshot of the developed framework - LCA

Table 3-7 Building systems demand and supply

	Demand	Supply	
		On-site	**Off-site**
Energy	Process (Plug Load) Lighting Space Heating Space Cooling Pumps Fans Service Water Heating Elevator	Wind Solar Geothermal Hydropower Biomass Tidal	Grid-connected
Water	Kitchen Shower Laundry Washroom Irrigation Mechanical heating/cooling	Groundwater Precipitation Source water	Municipal water
	Demand	**Low carbon footprint**	**High carbon footprint**
Building Materials	Building elements	Wood	Steel
		Glulam	Concrete
		Bamboo	Aluminum
		Linoleum	Vinyl

3.6 Natural Capital Assessment (NCA)

In Sections 3.2 to 3.5, the building demand for energy, water, and building materials is discussed. Natural capital assessment is performed in this step of the framework to identify the local natural resources available at the building's location.

3.6.1 NCA for Renewable Energy Sources

Buildings are capable of generating part or all of their energy demand from renewable energies. Renewable energy generation can take place within the building boundary (on-site) or outside of the building boundary (off-site). The goal of a NZB is to maximize the onsite renewable energy generation and rely on off-site renewable energy supply for the excess amount. Table 3-2 lists major renewable energy sources that can be used in buildings (Ellabban et al., 2014). Renewable energy forms include wind, solar, geothermal, hydropower, biomass and tidal. Among these, wind, solar, and geothermal are the main sources that can be used in buildings.

3.6.1.1 Solar Energy

Solar energy can be captured using Photovoltaic (PV) energy systems. PV energy systems convert solar energy to electricity. PV systems are usually installed on building roofs and can be fixed or have axial tracking to follow the location of the sun. PV potential of a building is directly correlated with the building's geographical location. Figure 3-11 shows the solar energy potential across Canada.

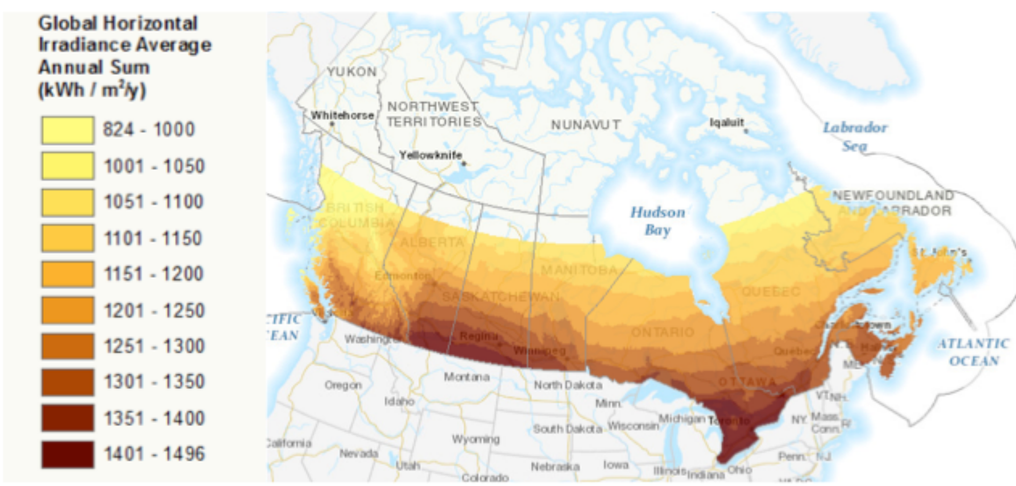

Figure 3-11 Solar energy potential in Canada (NRC, 2017)

In this framework, The National Renewable Energy Laboratory (NREL, 2015) PV calculator was used to calculate the annual solar energy potential for the building. Table 3-7 lists the main inputs required to calculate solar energy potential of NZB.

Table 3-8 Solar energy system design parameters

Parameters	Unit
Building Location	
Useable Area of the Roof	m^2
Additional Space Available for PV	m^2
Total Building Electrical Energy Demand	kW
DC System Size	kW
System Losses	%
Tilt Angle	degree
Electricity Cost Rate	$/kWh

3.6.1.2 Wind Energy

A wind turbine is a device that converts the kinetic energy of wind to electricity. Wind energy could be used as a reliable renewable energy source for NZBs that have outdoor space for wind turbine installation. Feasibility of wind energy mainly depends on the wind speed at the building's location. Annual wind energy potential can be calculated using equation 3-10:

$$\boldsymbol{WE} = 0.625 \text{ X } \boldsymbol{v}3 \text{ X } \boldsymbol{A} \text{ X } 8760 \text{ (h/year) X } 1/1000 \text{ (kW/W) X } \boldsymbol{eff}. \qquad \textbf{\textit{[Eq. 3-10]}}$$

where,

WE is the annual wind energy potential in kWh

v is the wind speed in m/s.

A is the area swept by the wind turbine blades (mostly circular). The area can be calculated by using the equation for the area of a circle: Swept Rotor Area = A = π X r^2 where r is the rotor radius.

Eff is the efficiency factor based on Betz's law. Betz's law calculates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow (Betz, 1966). Betz's law gives the maximal achievable extraction of wind power by a wind turbine as 59% of the total kinetic energy of the air flowing through the turbine. Most wind turbines have efficiency in the range of 35% to 40%. For this building, 35% efficiency was considered.

3.6.1.3 Geothermal Energy

Geothermal energy is the heat from the Earth. Almost everywhere, the shallow ground or upper 3 meters of the Earth's surface maintains a nearly constant temperature between 10° and 16°C. Geothermal heat pumps can tap into this resource to heat and cool buildings. In the winter, the heat pump removes heat from this layer and pumps it into the building. In the summer, the process is reversed and the heat pump moves heat from the building. This removed heat can also be used to heat domestic hot water (Renewable energy world, 2015).

The geothermal potential assessment in the NZB framework is conducted using the Climate Master Geothermal calculator (2015). Table 3-8 lists the input required for geothermal energy assessment.

Table 3-9 Geothermal energy system design parameters

Parameters	Unit
Building Location	
Outdoor Temperature	°C
Earth Temperature	°C
Annual Heating Energy Demand	kWh
Pumps Power	kW
Pumps Efficiency	%
System Losses	%

3.6.1.4 Other Renewable Energy Sources

Some of the renewable energy sources are mainly applicable to large-scale building projects. These energy sources include hydro, biomass, and tidal potential energy. Even though the following renewable energy sources are not currently used extensively in buildings, they have the potential to be used as viable energy sources in buildings and to help with the net zero target. This framework focused on the main renewable energy sources currently used in buildings.

Hydropower is derived from the energy of falling water, usually stored behind dams. Since the scale is larger than building scale, hydropower cannot be generated on site for small to medium scale buildings. Therefore, hydropower is excluded from the viable sources of renewable energy potential/natural capital on site for this building.

Biomass refers to the energy derived from plants. The most common type of biomass energy is the burning of trees for heat energy. Because this conventional process releases large amounts of carbon dioxide gasses into the atmosphere and is a major contributor to unhealthy air in many areas, it is not a viable source of renewable energy to reduce carbon emissions (Alternative Energy, 2015). The European Commission has published a report including information on current and planned EU actions to maximize the benefits of using biomass while avoiding negative impacts on the environment (European Commission, 2014).

Tidal energy is a form of hydropower that converts the energy of tides into useful forms of power, mainly electricity. Because tidal energy generation requires a large-scale plant and connection to source water, it does not fit for on-site building energy generation.

3.6.2 NCA for Water

NZBs can offset some or all of their water demand by capturing natural water supply within the building boundary. The NZB framework goal is to capture the maximum amount of water within the building boundary. The water demand can be captured from precipitation or groundwater.

3.6.2.1 Precipitation

Capturing precipitation is the most common way used in NZBs to provide the water that the building needs. Water from precipitation can be calculated from the following equation:

$$Precipitation\ water = PR \times A \times EF \qquad \textbf{\textit{[Eq. 3-11]}}$$

where,

PR is Precipitation Rate (m/yr)

A is Area dedicated to capture rain water through cistern or tank (m^2)

EF is Efficiency Factor.

The PR can be extracted from the Natural Resources Canada Precipitation Data (Natural Resources Canada, 2015). It is important to note that many governing bodies do not permit water captured from precipitation to be used for direct human consumption (including drinking, sink, shower, and kitchen) without water quality checks and treatments. Therefore, this water can either be allowed to sink into the ground to recharge water aquifers, or it can be stored in water cisterns on site for irrigation use, toilet flushing, and water services use (mechanical system heating/cooling).

3.6.2.2 Groundwater and Source Water

Groundwater is an essential resource that exists everywhere under the Canadian landscape. In Canada, 8.9 million people (30.3% of the population) rely on groundwater for domestic use. Groundwater's main use is in rural areas (Environment Canada, 2013). Buildings that are located in rural areas can rely on groundwater supply to offset their water demand.

The major constraint facing use of groundwater is municipality regulations. In many urban areas, the use of groundwater (through wells) requires permits from regulatory agencies, which can be a lengthy process. Also, in dense urban developments installation of a groundwater well and pump may not be feasible. Therefore it is very important to consider these constraints before counting on groundwater for buildings.

Another option of water supply for large-scale building projects is source water. Source water includes lakes, rivers, seas, and oceans that are located close to the building and from which the building can draw water. It can be a useful source of water supply for large-scale building projects that are located in close proximity to these water sources. To use source water for human consumption, the water needs to be treated according to the water standards and regulations that are in effect at the building's location.

Reuse of waste water is not included in the natural capital resources for this research due to human health risk concern. Waste water requires careful consideration because it needs to be treated to an acceptable level for human health contact as defined by the regulatory agencies. The quality of grey water can be assessed using Quantitative Microbial Risk Assessment (QMRA). QMRA has four stages: hazard identification, dose-response, exposure assessment, and risk characterization. For an in-depth review of QMRA, please refer to Zhang et al. (2012).

3.6.3 NCA for Sustainable Building Materials

Conventional building materials such as reinforced concrete and structural steel have a high carbon footprint. Excessive use of these materials can increase carbon intensity of the building. For the NZB framework, the focus is to rely on sustainable building materials that have low carbon intensity. NCA is used to identify sustainable building materials available at the building's location. These materials include building materials with low carbon intensity that can be used as structural members, including wood, glulam, and Cross Laminated Timber (CLT). Another group includes rapidly renewable building materials that can be used for building interior and finishes. The Canada Green Building Council (2016) identifies the following as rapidly renewable materials: bamboo flooring and plywood, cotton batt insulation, linoleum flooring, sunflower seed board panels, wheatboard cabinetry, wool carpeting, cork flooring, bio-based paints, geotextile fabrics, soy-based insulation, and straw bales (CaGBC, 2016). Other natural and local building materials such as clay and stone can reduce the impact of buildings.

3.7 Systems Integration

Once the analyses in Sections 3.2 to 3.4 are conducted to estimate the amount of resources the building consumes through its life cycle, NCA (Section 3.5) is done to evaluate the building's potential to support its needs. To reach net zero energy, the building's potential for generating renewable energy from all applicable forms should be evaluated. For net zero water, the building's potential to capture the amount of water it needs from precipitation, groundwater sources, and other bodies of water should be analyzed. Finally, LCA results can guide the design team to choose more sustainable building materials that have less carbon footprint.

A building is an integrated system and all of the three components (i.e. building materials, energy, and water) are interlinked. Therefore, the net zero target should cover all of these three aspects. In the proposed framework, results are represented in terms of their environmental impact (CO_2e) to overcome the variation in units among these three components. The energy is represented in CO_2e emission based on the source of energy generation. Similarly, water supply is characterized based on CO_2e emission of the water supply system. Finally, building materials are represented based on their LCA result of CO_2e emission.

Hence, a NZB in this methodology is defined as 'a building with net zero CO_2e emission throughout its life cycle,' as shown in Eq. 3-12:

$$Net\ Zero\ Building\ (NZB) = \sum_{t=0\ (cradle)}^{t=T\ (grave)} E_{CO_2e} + W_{CO_2e} + M_{CO_2e} \qquad \textbf{[Eq. 3-12]}$$

Where:

E is net-emission due to energy use

M is net-emission due to materials use

W is net-emission due to water use

T is building life span

Figure 3-12 shows the system integration step of the developed framework.

	tonnes of CO_2e
Energy	327
Water	33
Materials	0
Total	360

Figure 3-12 Snapshot of the developed framework – system integration

Equation 3-12 shows the life cycle impact of the NZB. If the result is greater than zero, it means that the building is not net zero carbon over its life cycle. To overcome this issue, an Offsite Carbon Offset Program is included in the NZB framework. The goal of this offsite program is to help buildings reach the net zero target in Equation 3-12.

Main ways to achieve offsite carbon offset include Renewable Energy Certificates (RECs) and Carbon Taxation. If the building does not have enough space to generate its energy demand through renewable sources on-site, the energy can be produced off-site through RECs. Renewable energy farms use renewable sources such as wind and solar to generate electricity and issue RECs for them. NZBs can purchase RECs as a means to offset their carbon footprint. A REC represents the property rights to the environmental, social, and other non-power qualities of renewable electricity generation (US EPA, 2015).

Carbon taxation can be imposed on the amount of carbon that a NZB cannot generate on site or offset. The amount of carbon taxation depends on the location of the building and environmental regulations. The Carbon Zero calculator (Carbonzero, 2016) is used in this framework to calculate the carbon tax of NZBs. Appendix B shows the steps of the NZB framework.

3.8 Life Cycle Cost (LCC) Analysis

In addition to an environmental assessment of using the natural capital for NZBs, the economic benefits of the building need to be evaluated and justified. For this purpose, LCC analysis is included in the framework. It is critical that the scope of LCC is coherent with LCA and Natural Capital Assessment (NCA).

There are various methods to conduct an economic analysis, including Net Present Value (NPV), Simple Payback (SP), Rate of Return (RoR) and Equivalent Annual Value (EAV). Among all of these methods NPV is the most effective in calculating LCC (European Commission, 2007). NPV is the sum of present values (PVs) of cash flows occurring at different stages of building (Petković et al., 2016). NPV analysis helps building stakeholders to consider the time value of money in the long-term building and construction projects. NPV is calculated as:

$$NPV\ (i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \qquad \textbf{[Eq. 3-13]}$$

where,

t is the time of cash flow,

i is the discount rate,

N is the number of time periods,

R_t is cash inflow or outflow at time

Figure 3-13 shows the LCC step of the developed framework.

LCC				
		Rt - Annual Cost savings ($)	**Life cycle cost savings ($)**	**Selected Design**
Energy	Solar	$29,243	$1,016,520	
	Wind	$472	$16,406	
	Geothermal	$21,512	$747,776	
Water	Precipitations	$15,876	$551,864	
	Groundwater	$6,024	$209,400	
Building Materials				
Carbon Offset cost			-$8,944	

Figure 3-13 Snapshot of the developed framework - LCC

Table 3-9 shows the main cost and benefits of NZBs. For this framework, RS Means Construction Cost Data (2016), published literature and reports are used to generate the cost estimates.

Table 3-10 Costs and benefits of NZB considered in the proposed framework

Costs	Benefits
Building materials	Energy savings
Energy	Water savings
Water	Carbon offset
Carbon Tax	

3.9 Implementation of the Framework

Equation 3-12 calculates the impacts of NZB based on the data used at the time of assessment. Quantity and quality of the data that is available for NZB assessment varies at different stages of a project life cycle. Figure 3-14 shows a typical life cycle of a project. The project life cycle starts with an Idea. At this stage the scope of building is defined, goal of the project is identified and project team members including owner, architect and engineers are formed. At the next stage, the project team evaluates various alternatives for the building. A feasibility study is then conducted to evaluate each of these alternatives with respect to the project's goal. This stage is called Feasibility. Once the preferred alternative is selected, the project team prepares a design concept for the building. The design concept is gradually improved to produce schematic design, working design and construction documents for the building. At this stage, the final building design is submitted to the authority having jurisdiction for review and approval (permitting stage). Upon approval, the building enters a procurement phase and then construction starts. The building operational phase starts after construction is completed.

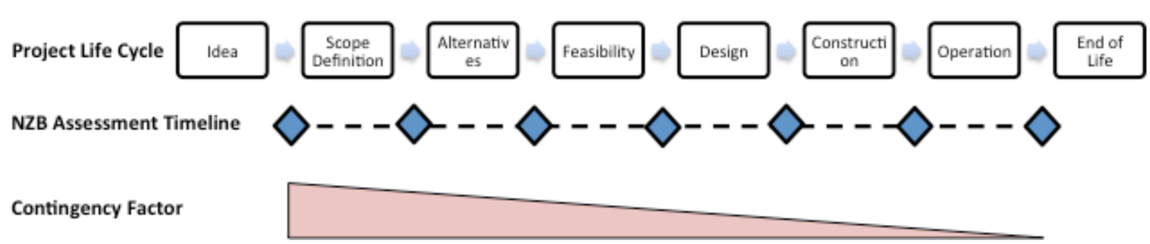

Figure 3-14 Project life cycle

NZB assessment should be conducted at each stage of the project life cycle based on the data that are available at that point of time. The accuracy of building data related to energy, water, building materials and natural capital increases during the project life cycle. For example, at the Idea stage, actual energy demand of the building is unknown and only a range is available. To account for the uncertainty in the data, a contingency factor should be considered in Equation 3-12. The contingency factor reduces as the uncertainty in the building data decreases.

NZB should be assessed in spatial-temporal dimensions. The spatial aspect is analyzed through availability of natural capital at the building's location. Type and amount of natural resources is not constant in the spatial dimension. For example, a building located in Kelowna, BC has access to more solar energy compared with a building located in Prince George, BC. This variation is shown on Figure 3-11. The temporal dimension deals with the accuracy of building data during the project life cycle. As discussed in Figure 3-14, accuracy of NZB assessment varies during project life cycle. For example at early stages of scope definition, NZB assessment includes a higher contingency compared with an assessment conducted at the construction stage.

It is important to distinguish project life cycle (as discussed above) from life cycle cost analysis and life cycle assessment. Life cycle cost analysis is a method to estimate economic feasibility of an option by calculating its costs during all life cycle stages. LCC assessment is discussed in Section 3.8. Life cycle assessment is a decision support method that helps building stakeholders calculate the environmental impact and carbon footprint of various options and select a sustainable option. LCA is discussed in Section 3.5.

3.10 Summary

The methodology developed in this chapter uses natural capital, net zero water assessment, net zero energy assessment, LCA, and LCC to evaluate net zero targets in buildings over their life cycle. The framework is composed of four steps. The first step defines a system boundary for the building and collects building data. Then, a demand assessment is conducted for three main components of the building: energy, water, and building materials. At the next step, natural capital assessment is performed to analyze the building's location for renewable energy, off-grid water, and sustainable building materials. The systems integration module uses outputs of the previous steps to identify the building's environmental footprint. A decision support tool is then used to identify how the building can become net zero carbon over its life cycle. The methodology aims to provide decision support to building stakeholders in the pre-design stage to evaluate sustainability options for implementation in the building's design.

In the next chapter, the methodology is applied for an LBC building to evaluate whether the building is net zero over its life cycle. Contributions of each of the building components are discussed and various scenarios are analyzed on how the building can get to net zero. Economic feasibility of each scenario is also evaluated.

Chapter 4. Net Zero Assessment of An LBC Building

To better grasp the idea, the methodology framework developed in Chapter 3 is used for net zero analysis of an LBC registered building in Canada (the building has not yet received LBC certification). Even though LBC is currently the world's leading assessment tool for NZBs, it has many drawbacks as noted in Chapter 2.

4.1 Study Area

The building selected for sustainability assessment is designed to achieve the LBC standard and be net zero. This building is a 7,335 m^2 institutional building located in Penticton, British Columbia, Canada (Figure 4-1). It is a 2-storey building that includes classrooms, offices, teaching workshops, a gymnasium, and an exercise area. The building sits on a 44,100 m^2 site and has a 5,455 m^2 roof area. The building's structural systems are composed of concrete and glulam (glued laminated timber). The building was completed in 2011 and is currently operational. The location of the building is surrounded by natural capital that can help the building toward its net zero target. The location receives a considerable amount of sunlight and precipitation.

Figure 4-1 Centre of Excellence building (Adapted from Okanagan College, 2015)

The main objective of this study is to evaluate the contribution of natural capital in achieving net zero CO_2e emission targets in the building. The contributions of water, energy, and materials are discussed and various scenarios for achieving net zero are evaluated. The building energy and water demand assessment was completed by professional engineers during the design phase of the building and were evaluated during the operational phase. LCA, LCC, and NCA are conducted to evaluate sustainability of the building.

4.2 Energy Use

The energy demand analysis for the building was completed by the building energy engineer using IES-VE 2012 software and was based on the ASHRAE 90.1-1999 standard. A third-party energy model review professional then verified the energy model. The building energy efficiency measures include:

- High efficiency lighting: the average lighting power density of 0.5-0.75 W/sf is used.
- Insulation: The U-value (Btu/h X ft^2 X F) for the project walls is 0.035 compared to 0.107 allowed by ASHRAE 90.1-1999. The U-value for the project roof is 0.0247 compared to 0.032 allowed by ASHRAE 90.1-1999.
- High efficiency glazing: The glazing assembly U-value for the project is 0.238 and Solar Heat Gain Coefficient (SHGC) is 0.55 compared to 0.57 U-Value and 0.42 SHGC allowed by ASHRAE 90.1-1999.
- Low window to wall ratio: The overall window to wall ratio of the building is 24%.
- Open-loop ground source heat pump: The basic source of heat for the building is a central ground coupled heat pump loop.

Table 4-1 shows the operational energy use of the building. Figure 4-2 shows life cycle energy use breakdown of the building, where 15% of the total energy consumption of the building over its life cycle is embodied energy, and 85% is the operational energy (Cole

& Kernan, 1996). As can be seen, space heating, lighting, and plug loads account for 88% of the building's energy consumption.

Table 4-1 Building annual energy use

Energy System	Energy Type	Energy Unit	
		MJ/yr	**kWh/yr**
Lighting	Electric	554,128	153,924
Space heating	Electric	895,377	248,716
Pumps	Electric	70,915	19,698
Fans	Electric	176,385	48,996
Service Water Heating	Electric	22,079	6,133
Plug Loads	Electric	645,499	179,305
Total		**2,342,304**	**650,640**

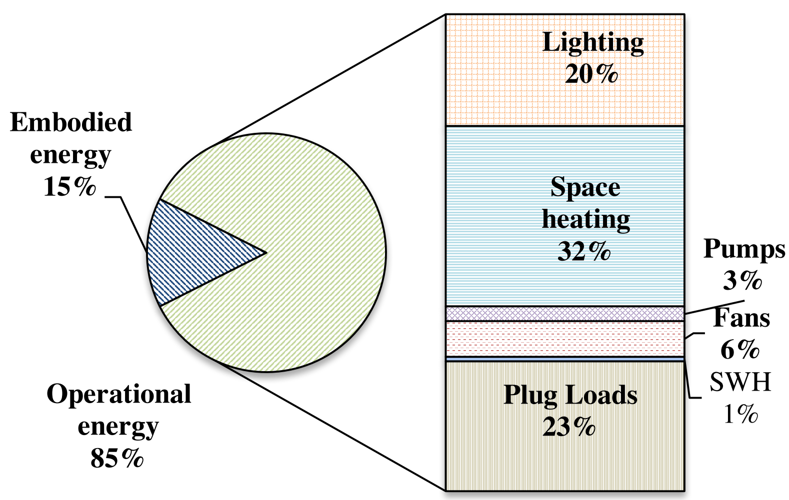

Figure 4-2 Life cycle building energy

So far, the E $_{Demand}$ component of Eq. 3-1 is identified. For conventional buildings, all of the energy demand is supplied from the grid (E $_{supply\ off\text{-}site}$). For the building, natural capital assessment is performed to evaluate the potential of renewable energy generation (the $E_{\text{supply on-site}}$ component in Eq. 3-1). The renewable energy can be supplied from the following sources:

4.2.1 Solar Energy

Solar energy can be captured using Photovoltaic (PV) energy systems. PV energy systems convert solar energy to electricity. PV systems are usually installed on building roofs and can be fixed or have axial tracking to follow the location of the sun. For this building, axial tracking solar panels are installed on the roof. The National Renewable Energy Laboratory (NREL, 2015) PV calculator was used in the framework to calculate the annual solar energy potential from this system (Table 4-2). Figure 4-3 show the annual solar energy potential of the building.

Table 4-2 Solar system design parameters

Design Parameters	
Area of the roof (m^2)	5,455
DC System Size (kW)	4
Module type	Standard
System losses (%)	14%
Tilt (degree)	20
Azimuth (degree)	180
Utility cost for the region ($/kWh)	0.1
Annual solar energy potential per year (kWh/yr)	292,432
Annual solar potential per area (kWh/yr/m2)	59.6

The solar system can generate energy throughout the year, where a minimum of 6,757 kWh was generated in December and a maximum of 39,194 kWh was generated in July.

Annual solar energy potential was 292,432 kWh and potential annual cost saving was $29,244 (electricity rate for the region is 0.1$/kWh).

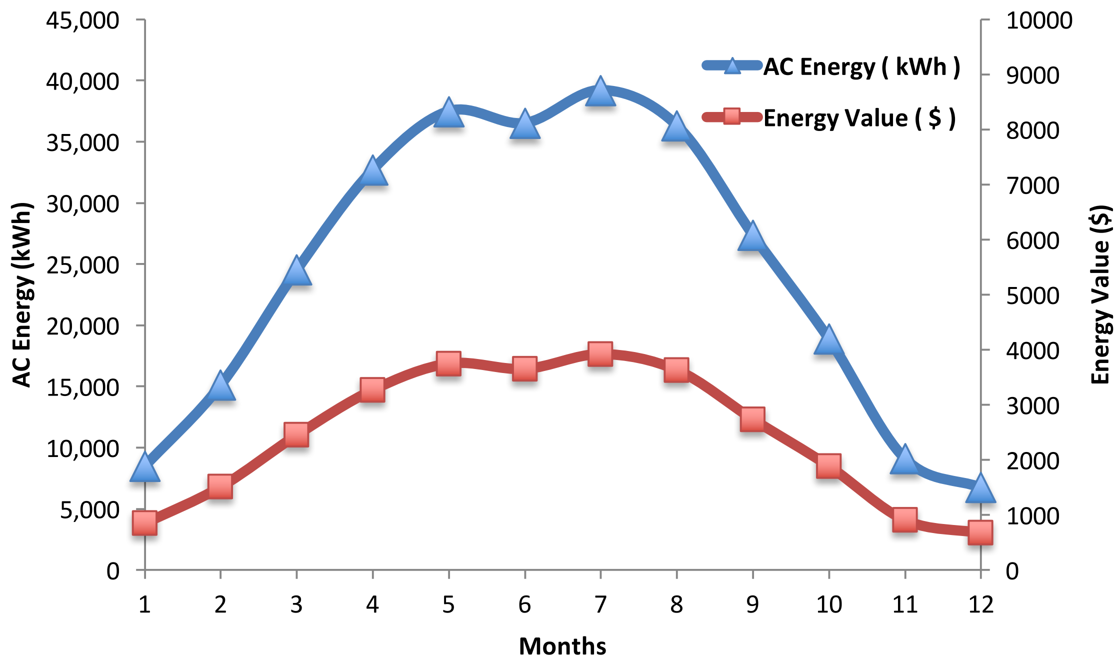

Figure 4-3 Annual solar energy potential

4.2.2 Wind Energy

As noted in Section 3.6, the feasibility of wind energy mainly depends on the wind speed at the building's location and area availability for the installation of the wind turbine. The building under study is located in an open space, with a large site area. Average annual wind speed for the location was 4 m/s (Windfinder, 2015). Annual wind energy potential is calculated based on equation 3-10:

Assuming small-scale wind turbine blade length of 3.5 meters, the WE for the building was:

$WE = 0.625\ 4^3 \text{ X } \pi \text{ X } 3.5^2 \text{ X } 8760/1000 \text{ X } 0.35 = 4{,}720$ kWh.

Wind energy potential was only 1.6% of the solar energy potential for the building's location. Annual cost savings by using wind energy is 4,720 kWh X 0.1 $/kWh = $472.

4.2.3 Geothermal/Geo-exchange Energy

The geothermal potential assessment in this framework is based on the Climate Master Geothermal method (2015). The result shows that the building has a potential of reducing its heating and cooling energy consumption by 53% by switching from the current heating and cooling system to a geothermal system (Table 4-3).

Table 4-3 Geothermal energy data

Design Data	Winter	Summer
Outdoor Temp (°C)	-10	33
Heating degree days (°C)	3484	
Earth Temp (°C)	11.4	
Current system annual heating energy consumption (kWh)	248,716	
Current system annual carbon footprint (metric tons)	6	
Geothermal system annual heating energy consumption (kWh)	117,228	
Geothermal system annual carbon footprint (metric tons)	2	
Geothermal system annual cost savings ($)	$21,512	

Figure 4-4 shows the energy demand and supply for the building. The building energy demand (650,641 kWh) was derived from Table 4-1. Solar energy supply was derived from Figure 4-3, and wind energy supply was calculated from Section 4.2.2. The Geothermal energy supply was calculated from Table 4-3 (248,716 – 117,228 = 131,488 kWh).

Two-thirds of the building's energy demand could be supplied from on-site renewable energy sources. The energy provided from the grid (222,000 kWh) is generated from a hydro-powered plant with a low emission intensity of 26 tonnes of CO_2e/GWh (WNA, 2015). Therefore, the proposed building energy system produced 5.8 tonnes of CO_2e annually. Assuming the building life span is 60 years, the building's total emission from energy systems is 348 tonnes of CO_2e ($\mathbf{E}_{CO2}$). This is a 66% reduction (from 1023 tonnes of CO_2e) compared to the building that is fully grid connected.

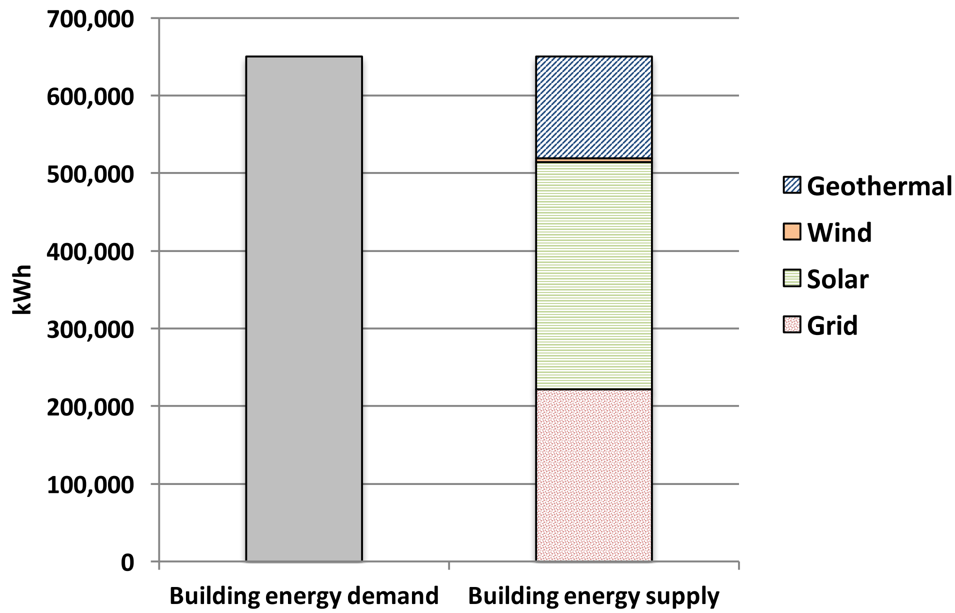

Figure 4-4 Building energy demand and supply

4.3 Water

The water demand assessment of the project was conducted by the building's professional engineering team during the design phase. The provided water use data is shown in Table 4-4 and 4-5. Indoor water use analysis is based on information developed by the U.S. EPA Office of Water based on requirements of the Energy Policy Act (EPAct) of 1992 and subsequent rulings by the US Department of Energy, requirements of the EPAct of 2005, and the plumbing code requirements as stated in the 2006 editions of the Uniform Plumbing Code.

The building's main water-saving features include:

- High efficiency water closets: 4.8 Liter per flush (LPF)
- High efficiency urinals: 1.9 LPF

- Low flow shower: 8.3 Liter per minute (LPM)
- Low flow lavatory and sink: 1.9 LPM
- High efficiency drip irrigation system

Table 4-4 Indoor water use demand analysis

Fixture	Flush/Flow fixture	Daily use	Flow rate (LPF or LPM)	Use duration (sec)	Occupant users	Annual work days	Annual water use (L)
Flush Fixtures	High efficiency water closet	4	4.8	-	250	230	552,000
	High efficiency urinal (male only)	2	1.9	-	125	230	109,250
Flow Fixtures	Low flow shower	1	8.3	300	50	230	477,250
	Low flow lavatory	3	1.9	12	250	230	65,550
	Low flow shop sink	1	1.9	15	250	230	27,312
	Low flow kitchen sink	20	6.8	15	5	230	39,100
	Janitors sink	5	9.5	15	5	230	13,656

- Total Flush fixture water demand is 661,000 L (661 m^3) and total Flow Fixture water demand is 623,000 L (623 m^3).

Table 4-5 Outdoor water demand analysis

Landscape Type	Area (m2)	Species Factor (Ks)	Density Factor (Kd)	Microclimate Factor (Kmc)	Landscape Coefficient (Kl = Ks*Kd*Kmc	Reference evapotranspiration rate (Et)	evapotranspiration rate (Etl) = Eto * Kl	Irrigation efficiency	Total potable water applied
Drought Tolerant Shrubs	751	0.2	1.0	1.3	0.26	178	46.3	0.9	38,618
Mixed plants	2298	0.5	1.1	1.4	0.77	178	137.1	0.9	349,960
Green roof native plants	827	0.2	1.0	1.3	0.26	178	46.3	0.9	42,526
Turf grass	631	0.7	1.0	1.2	0.84	178	149.52	0.8	117,934

- Total irrigation water demand is 549,000 L (549 m^3).

The building also requires 21,900 (m^3) of water for mechanical heating/cooling. The water can be captured on site from the two sources described below.

4.3.1 Precipitation

The building is located in the interior of British Columbia, Canada and receives a considerable amount of precipitation. The average annual precipitation rate for the building's location is 400 mm/yr (Natural Resources Canada, 2015). Multiplying the average annual precipitation by the total permeable site area and efficiency factor of 0.9 to account for losses, the annual precipitation on site is 15,525 m^3/yr.

This water can either be allowed to sink into the ground to recharge water aquifers, or it can be stored in water cisterns on site for irrigation use, toilet flushing, and water services use (mechanical system heating/cooling). For this building, the precipitation water was used for mechanical system cooling/heating (Table 4-6).

4.3.2 Groundwater

Groundwater is an essential resource that exists everywhere under the Canadian landscape. In Canada, 8.9 million people (30.3% of the population) rely on groundwater for domestic use. Groundwater is primarily used in rural areas (Environment Canada, 2013). The major constraint facing the use of groundwater is municipality regulations. For the building under study, groundwater use was permitted so the building benefited from this natural capital. For the considered building, 6,375 m^3 of water was drawn from the groundwater table annually.

The water demand/supply for this building is summarized in Table 4-6. The water supply from precipitation and groundwater were derived from Sections 4.3.1 and 4.3.2, respectively. The water used for the sink, shower, and kitchen (623 m^3) is supplied from the municipality (grid-connected).

Table 4-6 Water analysis data

Demand	**m^3/yr**	**Supply**	**m^3/yr**	**CO_2e (kg/yr)**
Flow Fixtures	623	Potable Water from the municipality (grid-connected)	623	193
Flush Fixtures	661	Grey water reuse from a WWTP	1,210	375
Irrigation	549	Groundwater	6375	0
Mechanical system heating/cooling	21,900	Precipitation	15,525	0
Water footprint of building materials	4,860			1,458
Total	**28,593**	**Total**	**23,860**	**2,026**

The water footprint of building materials is calculated using the LCA methodology described in section 3.4 and using water footprint data from Bribián et al. (2011). The building is located near a Waste Water Treatment Plant (WWTP) in Penticton, BC and is permitted to receive 1,210 m^3 of water from the WWTP. This grey water is only allowed to be used for toilet flushing and irrigation. The grid-connected carbon intensity was calculated from the SimpaPro LCA database as 0.31 g CO_2e /L of water. The average cost of water for the region is \$1/m^3.

The building can capture 21900 m3 (15,525 m^3 + 6,375 m^3) of water on site from precipitation and groundwater sources. This is 92% of the water demand for this building, resulting in \$21,900 annual cost saving. The annual CO_2e emission as a result of grid-connected and grey-water supply is 2.026 tonnes. Assuming the building life span is 60 years, the building's total emission from water systems is 121.6 tonnes of CO_2e ($\mathbf{W}_{CO2}$).

4.4 Building Materials

As described in Chapter 3, LCA is conducted to assess the impact of building materials. LCA consists of 4 interactive stages:

Goal and scope definition: The goal of this study was to assess the carbon emission of materials used in the building. The entire building envelope system, structural system, and flooring system are included in the assessment. The quantity of materials (Table 4-7) was extracted from the As-Built Architectural and Structural drawings.

Life Cycle Inventory: LCA was conducted using SimaPro software. Cradle-to-Grave is chosen as the system boundary and includes resource extraction, transportation, manufacturing, construction, operation and maintenance, and demolition stages.

Life Cycle Impact Assessment: In LCIA, the inventory was analyzed for its environmental impact. This study focused on Green House Gas (GHG) emissions in terms of CO_2e. The BEES (Building for Environmental and Economic Sustainability) method (NIST, 2009) was used for this analysis.

Table 4-8 shows the GHG emission of each building assembly over the life cycle of the building. As can be seen, total emissions of the building materials is 1,043,459 kg CO_2e, equivalent to 1043.459 tonnes of CO_2e over the life cycle of the building ($\mathbf{M}_{CO2}$).

Interpretation: The last step of LCA is to analyze and understand the result. As can be seen, structural systems that are made from reinforced concrete, including foundation, slab, and shear walls, have the highest CO_2e emissions and account for 61% of the impact. On the other hand, columns and roof joists that are made from glulam have a negligible impact (2%) and can be considered environment-friendly building materials. Glulam is a type of structural timber product comprising a number of layers of dimensioned timber bonded together with durable, moisture-resistant structural adhesives.

Table 4-7 Building materials quantity takeoff

System	Name	Quantity	Thickness (mm)	Width (mm)	Height (mm)	Total (m^3)	Material
Shear Wall	SW	28	13	100,650	10,950	401.17	Concrete
	SW	28	0.195	100,650	10,950	6.02	Reinforcement steel
Column	C1	20	175	266	10,950	10.19	Glulam
	C2	3	175	266	10,950	1.53	Glulam
	C3	6	175	304	10,950	3.50	Glulam
	C4	1	80	304	10,950	0.27	Glulam
	C5	6	175	604	10,950	6.94	Glulam
	C6	4	315	418	10,950	5.77	Glulam
	C7	35	350	266	10,950	35.68	Glulam
	C8	1	152	177	10,950	0.29	Glulam
	C9	1	130	114	10,950	0.16	Glulam
	C10	5	175	190	10,950	1.82	Glulam
	C11	2	215	266	10,950	1.25	Glulam
	C12	1	175	494	10,950	0.95	Glulam
	C13	1	130	228	10,950	0.32	Glulam
	C14	113	130	190	10,950	30.56	Glulam
	C15	1	130	266	10,950	0.38	Glulam
	C16	1	130	152	10,950	0.22	Glulam
Roof Joist	RJ6	17	130	380	8,100	6.80	Glulam
	RJ6	12	130	380	18,000	10.67	Glulam
	RJ3	9	130	380	25,920	11.52	Glulam
	RJ5	9	130	304	7,500	2.67	Glulam
	RJ8	12	130	494	10,000	7.71	Glulam

System	Name	Quantity	Thickness (mm)	Width (mm)	Height (mm)	Total (m^3)	Material
Slab	SB1		0.15	7,335		1100.25	Concrete
						22.01	Reinforcement steel
Roof	Roof asphalt		0.05	3,667.5		183.38	Asphalt
Façade	Cladding	391.8		0.24	10.95	1630.3	Metal
	Wood	391.8		0.24	10.95	1630.3	Wood
	Windows	391.8		0.24	10.95	1029.7	Glass
	Paint	391.8		0.24	10.95	3260.6	Paint
Flooring system	Hardwood		0.05	7,335		366.75	FSC Hardwood
	Plywood		0.05	7,335		366.75	2ply plywood
Foundation	Pile foundation	220	18.5	0.011		44.8	HSS Steel
		220.00	18.5	0.196		799.1	Concrete

4.5 Systems Integration

Equation 3-12 was used to estimate the building's CO_2e emissions throughout its life cycle and evaluate if the building is net zero emission:

$$\mathit{The\ Building\ impact} =$$

$$\sum_{t=0}^{t=60} E_{CO_2e} + W_{CO_2e} + M_{CO_2e} = 348 + 121.6 + 1043 = \boldsymbol{1,512.6\ tonnes\ of\ CO2e}$$

The energy and water impacts were reduced by more than 70% compared to the conventional grid-connected building by using on-site sustainable alternatives. Also, use of glulam as a structural element in the building has reduced the impact of the building materials, but steel and concrete are the main reasons for the high carbon footprint of the building. As a result, the LBC building is not net zero impact over its life cycle after integrating the three main systems (water, energy, and building materials). Figure 4-5 shows that building materials with 69% have the highest CO_2e emission impact over the life of the building, at about 3 times more than energy use (23%) and around 25 times more than water use (8%). As mentioned earlier, a major shortcoming of LBC is in ignoring the embodied impact of building materials. Many building materials such as concrete and steel have high carbon intensity. A true net zero emission building should include this in the assessment. The result emphasizes the importance of an integrated pre-design sustainability assessment that evaluates building materials, energy systems, and water systems.

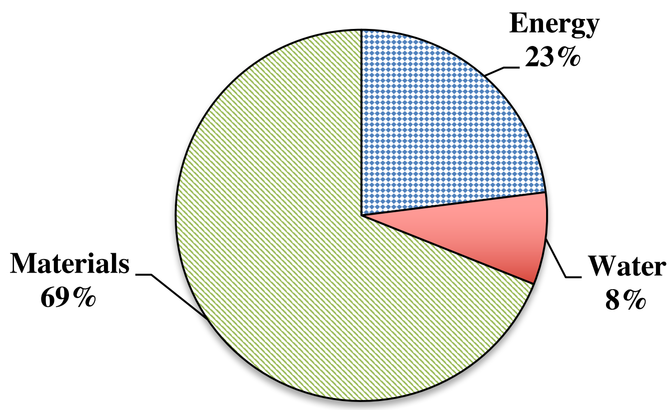

Figure 4-5 Emission by building components

The following scenarios are analyzed to bring the building to net zero impact.

4.5.1 Materials reuse

Steel and concrete can be recycled and reused in construction projects. On average, 85% of steel (World Steel, 2016) and 73% of concrete (Nisbet et al., 2003) used in the construction sector are recycled and reused. Assuming that steel and concrete materials are recycled at the end of their life cycle, CO_2e emissions from assembly will be reduced (Table 4-8).

Table 4-8 Global warming potential by assembly

Assembly	Main materials	kg CO_2e emission	kg CO_2e emission for Reuse Scenario
Shear Wall	Reinforced concrete, finishes	96,949	24,652
Column	Glulam	14,675	14,676
Roof Joist	Glulam	8,108	8,108
Slab	Reinforced concrete, finishes	277,505	69,352
Roof	Roof asphalt	90,448	90,448
Façade	Metal cladding, wood, glass windows, aluminum frame, paint	186,000	186,000
Flooring System	Hardwood, plywood, concrete	107,825	107,825
Foundation	HSS Steel, reinforced concrete	262,329	59,488
Total		**1,043,839**	**560,548**

The emissions from building materials for this scenario are 560.548 tonnes of CO_2e, a 46% reduction compared to 1043 tonnes of CO_2e for the base case.

4.5.2 Solar Canopy for the Parking Lot

To further reduce emissions from the energy systems, more renewable energy can be generated on site. The extra solar energy can be generated by installing solar canopies at the parking lot. The building has a 1700 m^2 parking area for a total of 50 parking spaces. Solar canopies can shield cars from heat and also generate electricity. Figure 4-6 shows the suggested area of a solar canopy installation.

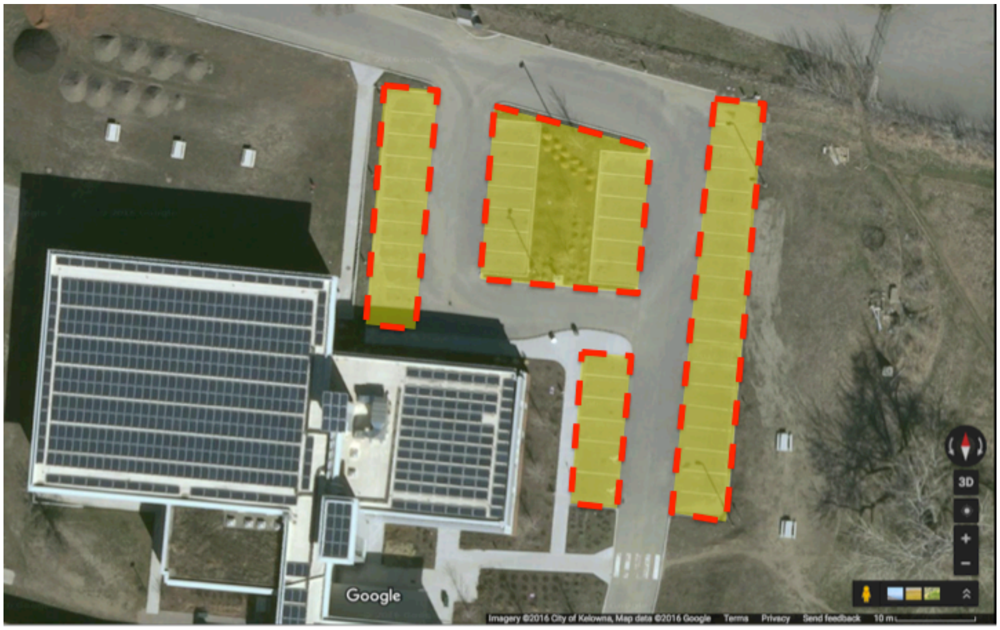

Figure 4-6 Suggested area for solar canopy installation (Google Maps, 2016)

Following the steps in section 4.2.1, the annual solar energy potential from the solar canopy is 222,000 kWh/yr. Therefore the building can produce 100% of its needed energy on site and does not need to rely on the grid (refer to Figure 4-4).

4.5.3 Offsite Carbon Offset Program

As mentioned in section 3.2.3, buildings can engage in off-site carbon offset programs to bring their net CO_2e impact to zero. The building can invest in off-site renewable energy generation through RECs. The building requires to offset 594 tonnes of CO_2e over its life cycle or 9.9 tonnes of CO_2e annually to be net zero. The average annual cost of carbon offset for the region is $24.86 per tonnes of CO_2e (Carbonzero, 2016). Figure 4-7 shows the sequence of reaching net zero CO_2e emissions for the building: the grid-connected building, the LBC design, materials reuse, solar canopy, and carbon offset.

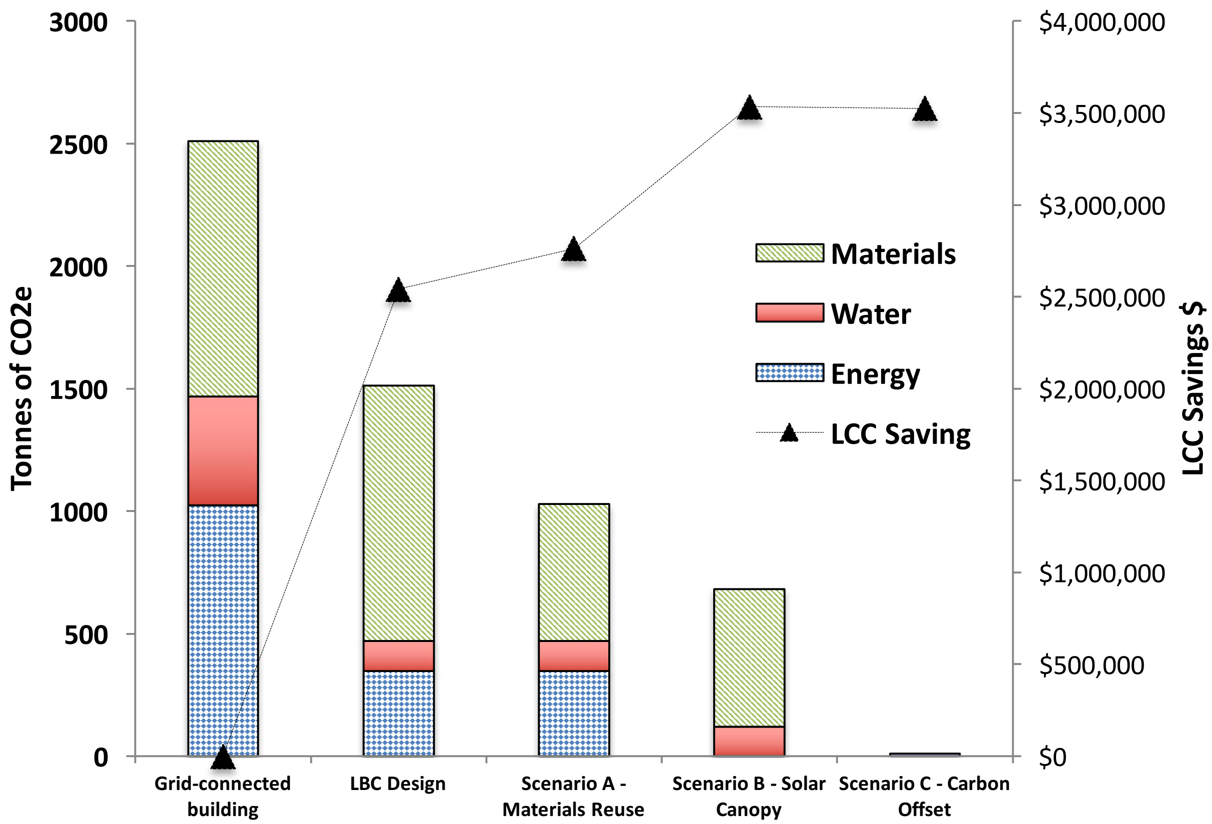

Figure 4-7 Net zero scenario and LCC analysis

4.6 LCC Analysis

As discussed previously, using the natural capital for NZBs can have economic benefits in addition to environmental benefits. A basic LCC is performed for the building to evaluate the economic benefits. Assuming i=2% (average annual inflation rate in Canada) and N=60 (life span of the building), the LCC savings is performed for the above-mentioned scenarios compared to a grid-connected building (Table 4-9).

As shown in Figure 4-7, the LCC savings for the assessed scenarios increases and the NZB will lead to $3.52 million over the life of the building. Solar energy accounts for 51% of total cost savings and has the highest potential for the NZB (Scenario 3). After solar energy, geothermal energy and water capture through precipitation account for 21% and 15% of life cycle cost savings, respectively.

Table 4-9 LCC analysis

Input	Grid-connected Building ($)	LBC Design ($)	Scenario 1 Materials Reuse ($)	Scenario 2 Solar Canopy ($)	Scenario 3 Carbon Offset ($)	Source
Solar Energy	0	1,016,547	1,016,547	1,788,239	1,788,239	Figure 4-4 and Section 4.2.1
Wind Energy	0	16,407	16,407	16,407	16,407	Section 4.2.2
Geothermal Energy	0	747,776	747,776	747,776	747,776	Table 4-3
Precipitations Water	0	539,663	539,663	539,663	539,663	Section 4.3.1 and Section 4.3.3
Groundwater	0	221,601	221,601	221,601	221,601	Section 4.3.2 and Section 4.3.3
Materials Reuse	0	0	220,940	220,940	220,940	Assuming 85% of steel will be recycled
Carbon Offset Cost	0	0	0	0	-8,551	Section 4.5.3
Total	**0**	**2,541,994**	**2,762,934**	**3,534,626**	**3,526,075**	

4.7 Summary

For sustainable development, the building and construction sector needs to move toward net zero and self-sufficient buildings. However, the current NZB rating system (LBC) has major drawbacks. The scope of LBC is limited to identifying what net zero is and does not provide a guideline for how to achieve net zero. It does not offer a clear methodology for how a building can achieve net zero targets using local resources. The methodology is not adaptable and does not take the location of building into consideration. Also, current NZB rating systems do not consider the full life cycle impact of buildings in their assessment.

In this chapter, the methodology that was developed in Chapter 3 is demonstrated through an LBC-registered building. The result indicates that the LBC design is not net zero CO_2e over the life of the building. Building materials with 69% have the highest

CO_2e emission impact over the life of the building, but the embodied impact of building materials is not considered in LBC. Building materials with high carbon intensity such as concrete account for a considerable portion of the impact. The methodology considers the entire life cycle of buildings and evaluates whether the building is net zero in this timeframe. Table 4-10 shows a summary of comparison between the developed framework and LBC.

Table 4-10 Comparison of developed framework and LBC

	Developed Framework	Existing NZB Rating System (LBC)
Target	NZBs	NZBs
Type	Assessment and decision support tool in pre-design stage	Assessment tool in design stage
Energy	Net zero over life cycle of the building through both off-site and on-site renewable sources. Unit: CO_2e	Net zero on an annual basis through on-site renewable sources. Unit: MJ
Water	Net zero over life cycle of the building through use reduction and water harvesting. Unit: CO_2e	Net zero water on an annual basis supplied by captured precipitation or other natural closed loop water systems. Unit: L
Sustainable materials	Life cycle assessment of building materials Unit: CO_2e	Avoid the Red List materials Unit: g
Integration of the modules	Yes	No
Geographical consideration	Yes	No

Various scenarios are considered to bring the building to net zero CO_2e emission over its life cycle. The result shows that the building can become net zero CO_2e emission over its full life cycle by investing more in renewable energy and with the help of materials recycling and an off-site carbon offset program. The building can generate 100% of its energy from renewable energy sources. Among the renewable energy sources, solar and geothermal have the highest energy generation potential for the building's location. The solar energy is captured using solar photovoltaic system. Besides energy, the building can capture 92% of its water needs on site using closed-loop water systems from precipitation and groundwater. Moreover, using glulam as a structural element in the building helped to reduce the carbon footprint of building materials significantly.

Besides environmental benefits, using natural resources can have significant cost savings for the building. LCC analysis shows that life cycle cost savings for the building add up to more than $3.5 Million.

Buildings are designed to last for a long period (40-100 years). Thus, much of the actual energy and water use data are not available at the time of the sustainability assessment, which takes place at very early stages of the design or operation phases of the building. Therefore, it is critical to conduct the net zero assessment at various milestones throughout the project's life cycle: feasibility stage, scope definition, design, construction, and continuously during operation. The net zero framework parameters, including the emission conversion factors and system efficiencies could change over time and impact the net zero output (Equation 3-12).

Furthermore, sustainability decision-making is based on a vast amount of data that might not be readily available. To enhance the accuracy of sustainability analysis or decision-making, detailed uncertainty analysis in performed in Chapter 5.

Chapter 5. Uncertainty Analysis of the NZB Framework and Policy Suggestions

This chapter consists of two parts. The objective of the first part is to review the sources of uncertainty in NZB assessment and study their impacts in the developed NZB Natural Capital Assessment Framework. This research is intended to help building stakeholders understand the uncertainty involved with sustainability assessment frameworks. The chapter aims to highlight parameters with the highest contribution in sustainability of buildings so stakeholders can invest their efforts in the right direction.

In the second part of this chapter, based on the results of uncertainty analysis and the NZB assessment framework, some NZB policy recommendations are made. NZB has been used in many countries as one of the main government strategies for addressing climate change and other environmental challenges (Pan & Ning, 2015). Despite the fact that NZBs are critical for sustainable development and many buildings worldwide have been designed and constructed towards zero carbon (Pan & Li, 2016), there are only a limited number of NZBs in the province of British Columbia (BC) in Canada. A comprehensive literature review of what drives the adoption of green building practices among construction stakeholders (Section 2.4) shows that the main driver of NZB is 'government regulations and policies' (Darko et al., 2017). Existing sustainable building policies and regulations in the province of BC were reviewed in Section 2.4. The review showed that there is a need for a NZB policy in the province. In this chapter, Game Theory is used to provide NZB policy suggestions. The suggested NZB policy aims to close the gap for fair distribution of life cycle cost and benefits of NZB among the building stakeholders including the developer, public, and government.

5.1 Uncertainty Analysis

The statistical approach was used to study uncertainty in the developed NZB framework. The NZB results (as discussed in Chapter 4) showed that the building under study was not net zero over its life cycle and will produce 1,512.6 tonnes of CO_2e over its life. The NZB assessment result indicated that building materials with 69% have the highest CO_2e emission impact over the life of the building, about 3 times more than energy use (23%) and around 25 times more than water use (8%). The study evaluated various scenarios that could help the building reach net zero target.

In the following sections, the three types of uncertainty associated with the framework are discussed and results are analyzed.

5.1.1 Parameter Uncertainty

Error in the value of input data causes parameter uncertainty. When designing sustainable buildings, there are many parameters that are unknown, unavailable, or imprecise. These parameters belong to the energy system, water system, and the natural capital resources.

The first concept and arguably the most important component of sustainable buildings is the energy system. The energy system covers all of the building sub-systems that consume energy, including lighting, space heating/cooling, pumps, fans, service water heating, and plug loads. The energy system consists of many parameters, which are used as input data for a BEM tool to estimate the energy consumption of the building thorough its life cycle. Table 5-1 shows the main parameters of the building energy system.

5.1.1.1 Energy Parameters

Energy parameters that are associated with the design and construction of the project are less uncertain because their values are based on more reliable and accessible input data at the early stage of the building life cycle. For example, window-to-wall area ratio is an important factor affecting the energy performance of the building. This parameter is calculated by dividing the total area of the openings in the building envelope (doors, windows) by the total area of the building envelope. A 40% window-to-wall ration indicates that the building envelope has 40% opening area. This parameter is calculated during the design phase of the building based on reliable input data. Therefore, it has a high accuracy value.

Table 5-1. Energy system main parameters

Sub-system	Parameter
Building Envelop	Window-to-wall-area ratio (%) Overall window USI-value (W/m²°C) Window shading coefficient Overall wall RSI-value (m²°C/W) Gross exterior wall area (m²) Roof type Overall roof RSI-value (m²°C/W) Gross exterior roof area (m2)
Mechanical System	Heating efficiency (%) Minimum outside air (L/s/m²) Demand control ventilation (DCV) type Percent of outside air controlled by DCV (%) Percent of floor area cooled (%) Cooling efficiency (COP) Efficiency of exhaust air heat recovery (%) Service water heating fuel type Service water heating efficiency (%) Service water savings (%)
Lighting System	Average lighting density (W/m2) Lighting control (% of floor area) % of lighting load with occupancy sensor control (%)
Process Load	Average process load density (W/m2) Percent served by electricity (%)
General	Source of energy supply in the region Primary heating system

In contrast, parameters related to user behaviour during the operational phase of the building are less certain and are based on less reliable information. The building energy systems can be sub-divided into process and non-process energy systems. Process energy refers to energy used by equipment and appliances in a building, which is difficult to predict and involves a higher degree of uncertainty. Average process load density calculates the amount of energy consumed by appliances. These plug loads include home appliances such as refrigerators and dishwashers, as well as personal computers and TVs. On average, plug loads account for 30% of electricity consumption in offices (Moorefield et al., 2008). Based on the design of office buildings, the plug loads can range from 25% to 50% (Poll & Teubert, 2012).

In the case study building, the plug load was modeled as 27%. A range of 25% to 50% is used to account for the uncertainty of this parameter. Figure 5-1 shows the net emission results of the building for three cases: lower end (25%), middle (37.5%), and higher end of the range (50%). Net emissions of the building increase significantly (1592 tonnes of CO_2e) for the upper range of the plug load. This means that the building should generate more on-site renewable energy to offset the impact of this increase in CO_2e emission.

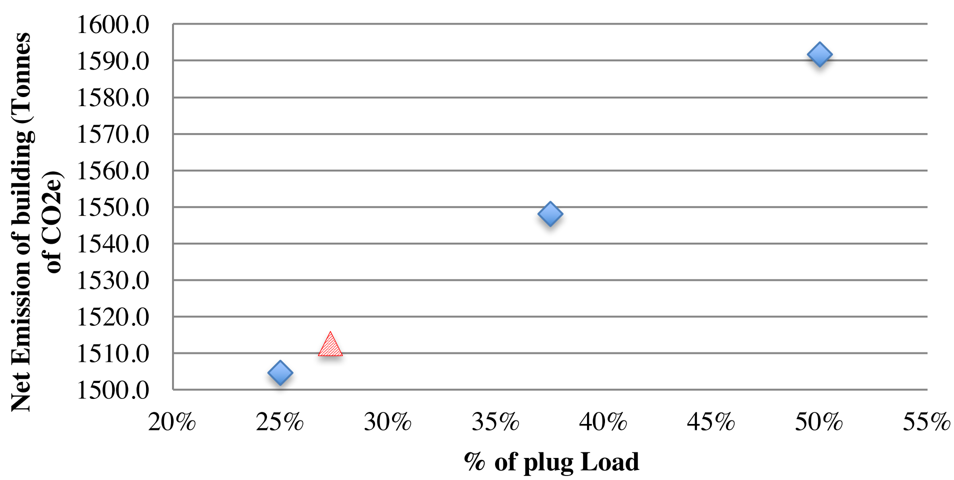

Figure 5-1 Net emission of the building for a range of plug loads

5.1.1.2 Water parameters

Water-efficient systems help to lower the water consumption of buildings. NZBs aim to capture most of their water needs on site. Table 5-2 includes the main parameters of a building water system. The water system can be categorized into indoor water, outdoor water, and process water systems.

From the parameters listed in Table 5-2, ‘number of daily use,’ ‘use duration,’ and ‘number of occupant users’ are the most uncertain parameters (Equations 3-6, 3-7, and 3-8). These parameters can vary significantly based on the behaviour of building occupants.

Table 5-2. Water system main input parameters

Indoor Water	Number of daily use Flow rate (LPF or LPM) Use duration (sec) Number of occupant users Annual work days
Outdoor Water	Landscape Type Species Factor (Ks) Density Factor (Kd) Area (m2) Microclimate Factor (Kmc) Landscape Coefficient Evapotranspiration rate (Etl) Irrigation efficiency (IE)
Process Water	Mechanical heating/cooling water demand (L)

Uncertainty analysis is therefore performed to consider a range for each of these parameters. Figure 5-2 shows the result of water emission and total emission by changing these parameters. An upper-end and lower-end value for each of the uncertain parameters are selected and water calculation is performed to estimate annual water use.

The total emission for maximum daily use could increase the total emission of the building by 259 tonnes of CO_2e to 1771.6 tonnes of CO_2e. This is more than the maximum emission due to an increase in energy parameter (1591.6 tonnes of CO_2e in Figure 5-1). This is an interesting result considering that water contributed less to the emission of the building than energy in the case study building.

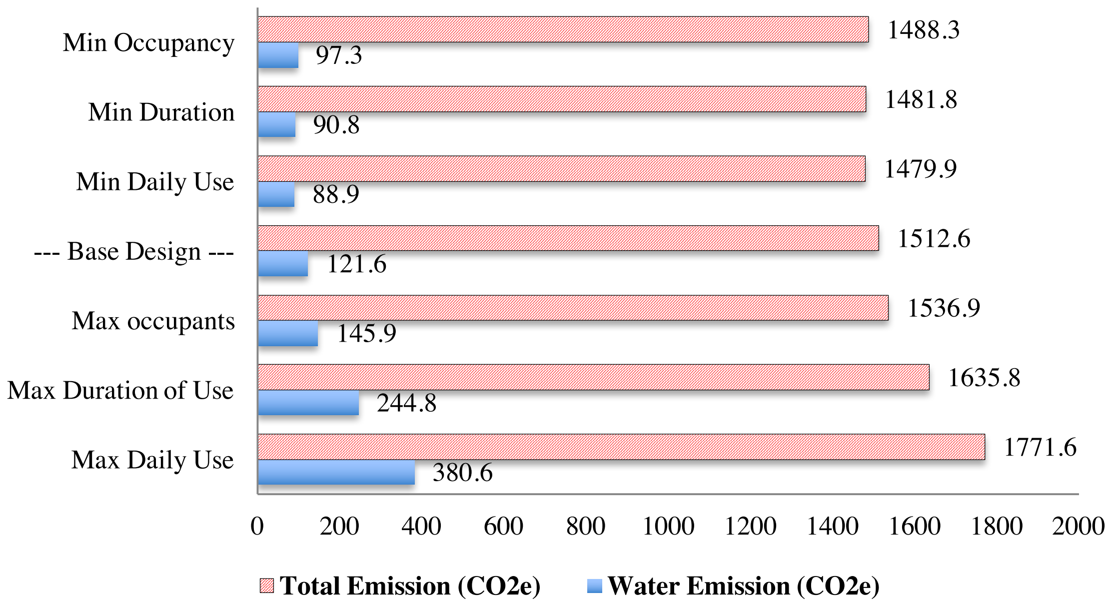

Figure 5-2 Impact of water parameters on total emission

5.1.1.3 Natural Capital Parameters

NZBs use natural capital to become self-sufficient. The natural capital available for use in buildings varies according to their location. Table 5-3 lists the main parameters of natural capital and related sustainable building systems.

From the parameters listed in Table 5-3, parameters that rely on past data to predict future results are most uncertain. These include annual precipitation rate, annual solar energy potential, and average annual wind speed. Lack of data for these parameters causes uncertainty in the amount of natural capital available for the building during its operation.

The National Renewable Energy Laboratory (NREL, 2015) PV calculator was used to calculate the annual solar energy potential for the building. To account for the uncertainty, a range of solar potential for the building location was used. The result shows that the solar energy the building can generate varies significantly, as shown in Figure 5-3. The error bar indicates the range of solar energy output based on a range of annual solar energy potential.

Table 5-3. Main parameters of natural capital

Wind Energy	Average annual wind speed (m/s) Wind power density (w/m2) Wind turbine efficiency
Solar Energy	Annual solar potential per area (kwh/m2) System size (kw) Module type System efficiency Tilt (degree) Azimuth (degree)
Geothermal Energy	Outdoor temp in summer (degree C) Outdoor temp in winter (degree C) Heating degree days (degree C) Earth temp (degree C) System efficiency Quality of insulation
Water from Precipitation	Average annual precipitation rate (mm/yr): Water capture capacity (m2)
Groundwater	Groundwater availability (L) Pump efficiency

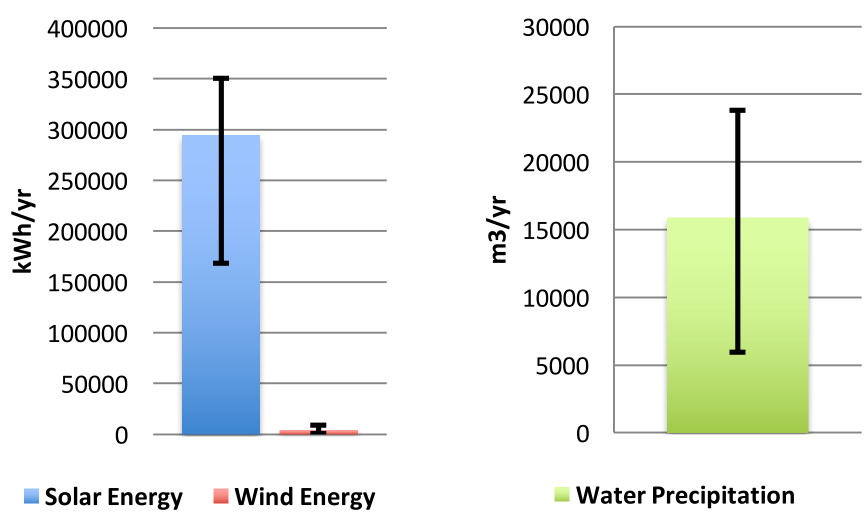

Figure 5-3 Uncertainty in natural capital resources

For the wind speed, average wind speed for the location of the building is 4 m/s (Windfinder, 2015), which results in annual wind energy of 4,720 kWh. Changing the wind speed to 5 m/s results in a 95% increase in the amount of wind energy generation, to 9,218 kWh/yr. The wind speed of 2 m/s reduces the wind energy potential to only 590 kWh.

The average annual precipitation for the building's location is 400 mm/yr (Natural Resources Canada, 2015), which results in annual precipitation of 15,876 m3 on site. Precipitation can range from 150 mm to 600 mm, resulting in water savings of 5,953 m3/yr to 23,814 m3/yr.

5.1.2 Model Uncertainty

This section discusses the impacts of model uncertainties associated with the NZB framework.

5.1.2.1 LCA

Even though LCA is a very powerful method to estimate environmental impacts for decision-making, uncertainty is a fundamental part of the LCA model that makes extraction of reliable results more challenging. It is important to note that the objective of uncertainty assessment of LCA results is not to criticize the method rather to manage expectations of the outcome. Heijungs and Suh (2002) studied LCA and its related uncertainties.

The first step in LCA is defining the boundary of the study. The boundary is a critical component of every LCA study, because it defines the extent of the study. It outlines what environmental impact categories are considered, and what parameters and systems are excluded from the LCA scope. This ambiguity in the scope of a LCA creates uncertainty.

Life cycle inventory (LCI) analysis is the next step of a LCA study. In this step, system inflows and outflows are calculated. Spatial and temporal variety between the available data and actual input data is another cause of uncertainty in LCA models. Site-specific data are not always available and therefore LCA practitioners rely on standard LCI databases such as Ecoinvent to estimate the inflow and outflow of their systems. This process leads to uncertainty because the data from LCI databases may not accurately reflect the process of the study. Data might be missing from the database or it may be created for different environments and conditions. For example, in analyzing concrete used in a building in Canada, data might be based on concrete manufactured under different conditions, with a different material composition in a different country.

Results of the LCI analysis are fed to the life cycle impact assessment (LCIA) stage of LCA. At the LCIA stage, a set of impact categories are selected and impacts are calculated using one of many LCIA methodologies. This process leads to uncertain outcomes, as selection impact categories and LCIA methodologies are not unique.

LCA is used to assess the carbon emission of building materials. The quantity of materials was extracted from the As-Built Architectural and Structural drawings, and the LCA was conducted using SimaPro software. Cradle-to-Grave was chosen as the system boundary, which includes following stages: resource extraction, transportation, manufacturing, construction, operation and maintenance, and demolition. In Hossaini et. Al. (2017), SimaPro was used to conduct the analysis based on the Ecoinvent database. To account for uncertainty in data, LCA was repeated using the Athena Impact Estimator (2016) to compare the results. Results of both analyses are shown in Table 5-4, under Scenario 1 (Scenario 2 is discussed in Section 5.2.4).

Table 5-4. Uncertainty in LCA

		Scenario 1		Scenario 2
Assembly	**Main Materials**	**kg CO_2e Emission - SimaPro**	**kg CO_2e Emission - Athena Impact Estimator**	**kg CO_2e Emission Reuse Scenario**
Shear Wall	Reinforced concrete, finishes	96,949	108,467	24,652
Column	Glulam	14,675	14,295	14,676
Roof Joist	Glulam	8,108	8,108	8,108
Slab	Reinforced Concrete, finishes	277,505	308,620	69,352
Roof	Roof asphalt	90,448	110,025	90,448
Façade	Metal cladding, wood, glass windows, aluminum frame, paint	186,000	186,000	186,000
Flooring System	Hardwood, plywood, concrete	107,825	107,825	107,825
Foundation	HSS Steel, reinforced concrete	262,329	282,453	59,488
Total		**1,043,839**	**1,125,793**	**560,548**

The results of these two assessments differ by 7.5%. This shows that using different LCA tools and LCI databases impacts the CO_2e emission calculation.

5.1.2.2 LCC

The financial feasibility of NZBs is often evaluated through LCC analysis. Similar to LCA, LCC models rely on a set of current data to calculate future outcomes. The main uncertainties in LCC of NZB assessment are as follows:

- Not considering all of the associated costs
- Interest rate and rate of return value
- Building life expectancy
- Assumption about future costs

An LCC analysis was performed using the NPV method. NPV is the sum of present values (PVs) of cash flows occurring at different stages of a building. NPV is calculated using Equation 3-13. A range of 1%-4% is considered for i, and a range of 50-70 years is considered for N (building life expectancy). Figure 5-4 shows the results of the NPV for LCC sensitivity analysis.

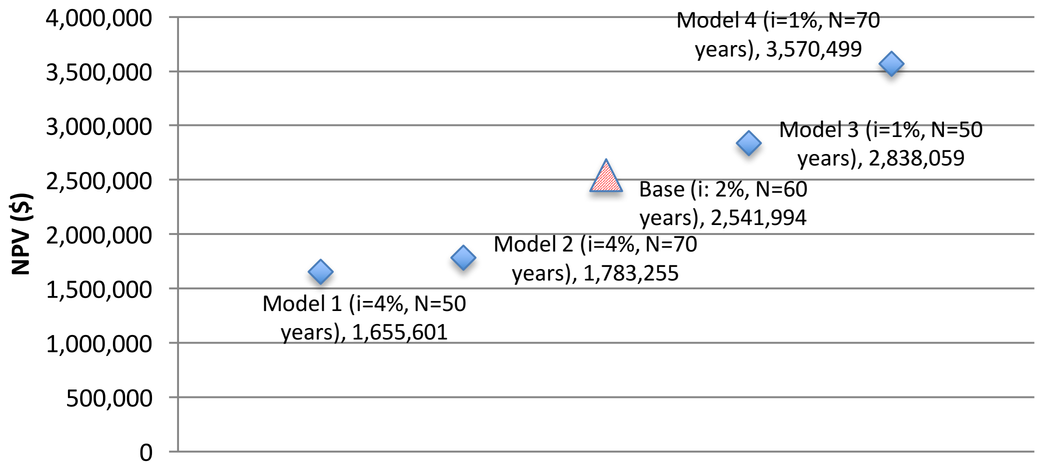

Figure 5-4 Uncertainty of LCC model

The result indicates that NPV is highly sensitive to discount (interest) rate. In the base case, the average annual inflation rate of Canada (2%) is used. Changing this value to 1% significantly increases the NPV of the NZB. The building life span also plays an important part in the NPV of the building in that the longer the building is operational, the greater the financial benefits.

5.1.2.3 Natural Capital

Similar to LCA and LCC, the natural capital framework for NZBs has a defined boundary. Some natural capitals are excluded from the framework, which causes uncertainty in the outcome of study. In this framework, the main renewable energy sources that are used in buildings are considered. These include solar, wind, and geothermal. Other sources of renewable energy that are mainly applicable to large-scale projects are excluded from the scope (system boundary). These energy sources include hydro and tidal potential energy. These renewable energy sources are not currently used extensively in buildings but have the potential to be used as viable energy sources in buildings in the future, when the technology becomes more feasible.

Hydropower is derived from energy of falling water, usually stored behind dams. Creating small-scale dams to generate electricity for a single building is not a feasible technology. However, with technology and science advancements it may become a reasonable option later in the life span of a building. Similarly, tidal energy can become feasible in the future. Tidal energy is a form of hydropower that converts the energy of tides into useful forms of power, mainly electricity. Conventional tidal energy generation requires a large-scale plant and connection to source water, so it does not fit for on-site building energy generation.

5.1.3 Scenario Uncertainty

This section discusses the impacts of scenario uncertainties associated with the NZB framework.

5.1.3.1 End-of-life Use of Building Materials

NZBs have a finite life span. At some point the building will not be functional economically, environmentally, or could pose a safety hazard to its occupants. That stage is called the end-of-service-life of a building. Buildings can have various end-of-life scenarios. Building materials and other components such as electrical and mechanical systems can be sent to landfill, reused in other buildings, or sent to recycling facilities to be recovered and form a new product. The end-of-life stage of a building is a major cause of uncertainty in NZB assessment because most of the time little or no information is available on the end use of the building while assessing for net zero. Also, the decision about end use can change during the life span of the building. Therefore, it is logical to consider multiple end-of-life scenarios.

To consider the impact of end-of-life scenarios, two scenarios are considered. The first scenario assumes that building materials are sent to a landfill at the end of their life. The second scenario assumes that some of the steel and concrete is recycled for reuse in other construction projects. On average, 85% of steel (World Steel, 2016) and 73% of concrete (Nisbet et al., 2003) used in the construction sector are recycled and reused. Table 5-5 shows the emission of building materials for these two scenarios. The emission of building materials for Scenario 2 is reduced significantly to 560.5 tonnes of CO_2e, a 50% reduction compared to Scenario 1 (average of the two models).

5.1.3.2 Climate Change

If not managed properly, climate change and global warming will have a severe impact on the earth. Climate change and global warming will change the landscape of natural capital and its availability. This serious threat could affect the energy and water supply for NZBs in the future. The amount of rainfall, solar irradiation, and wind energy potential that a NZB receives could be impacted by climate change. There are not enough data and models currently available to analyze the uncertainty of climate change for NZBs.

5.1.3.3 Geopolitical

NZBs are designed to last for a long period of time (50-75 years). During a lifespan of a building, many geopolitical changes might happen that could directly impact supply and demand of building resources during the operational phase. Variation in the price of energy, carbon taxation, political conflicts impacting availability of resources, and governmental changes to environmental policy are among the many uncertainties that can impact a NZB assessment.

5.2 Net Zero Building Policy Suggestions

There are three main stakeholders in sustainable building policies. The first stakeholder is the builder who plans to construct the building. The builder may be a public organization, a private entity, or a public private partnership (PPP). The second stakeholder is the future building occupant or building user. The building occupant may be public, private, or a mix of both public and private groups of people. The final stakeholder is the local government that reviews the builder's request to construct a building, and evaluates the application against the building code, bylaws, policies, and regulations. The local government then makes a decision to issue a building permit for the builder or deny the application.

Sustainable and net zero buildings have better energy and environmental performance than conventional buildings due to their use of more efficient building materials, envelopes, and energy systems. These efficient systems typically cost more than the minimum systems required by the building code, and as such there is a cost premium at the beginning of building construction. These upgrades will help the building to reduce energy and water consumption during its operational phase and require less maintenance for the systems and equipment. Therefore, sustainable buildings will benefit from this initial investment and save cost during the use phase. Studies show that NZBs are more cost effective than traditional buildings over their respective life cycles (Hossaini et al., 2017). Buildings produce a large proportion of GHG emissions in urban areas across Canada, and local governments control a number of policy levers that can help to reduce those emissions (Schwartz, 2016).

The major challenge for implementing a sustainable building policy is the fair distribution of costs and benefits among the key stakeholders. As noted, sustainable building costs more for the builder who is only involved at the construction stage of the building and cannot benefit from cost savings during the use phase of the building. Figure 5-5 shows a typical involvement of key stakeholders over a building life cycle and distribution of costs and benefits.

As can be seen, a builder who is involved in planning, design, and construction of the building does not benefit from the cost saving during the operational phase if the ownership transfers. Therefore the builder has little or no motivation to implement net zero targets. To address this issue, NZB policy suggestions are provided that consider a fair distribution of cost and benefits for each stakeholder. The following are the three main steps to develop these policies.

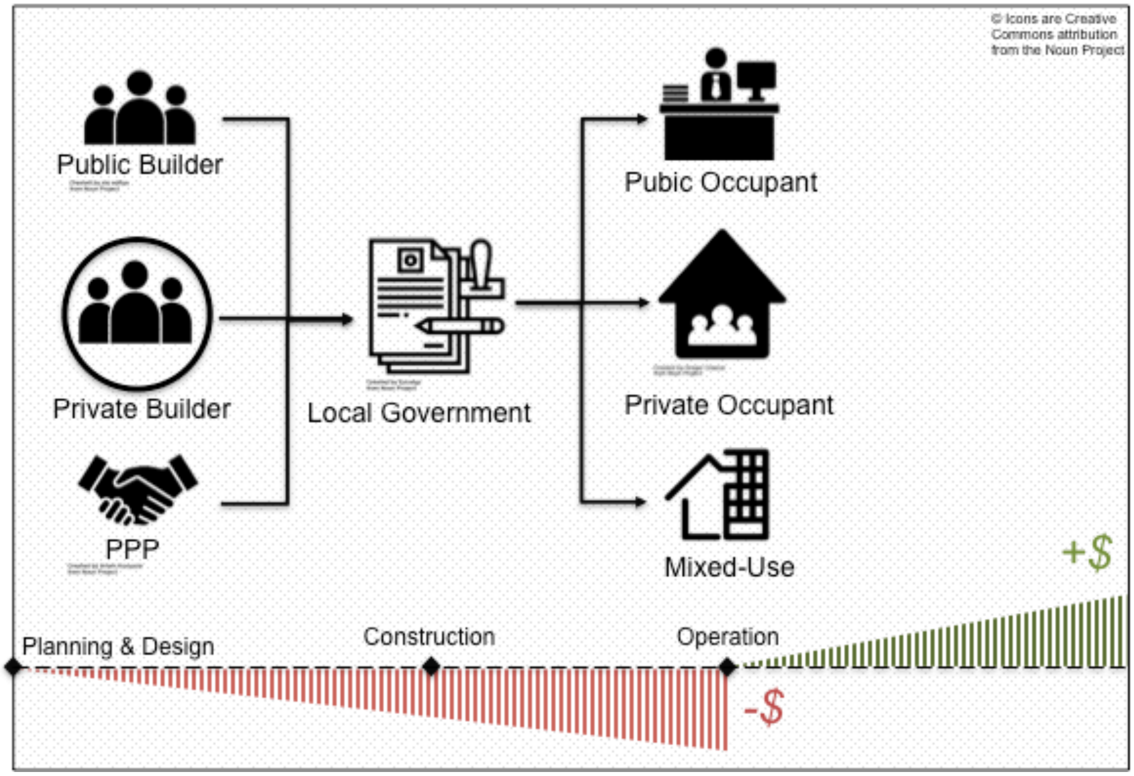

Figure 5-5 Typical involvement of building stakeholders over life of a building

5.2.1 Goal and Scope Definition

The NZB policy has three components. First, it identifies net zero as a target for new building construction. The policy aims to reduce the environmental impacts of the built-environment by ensuring new buildings have net zero carbon impact. Also, the policy identifies how to measure net zero based on the NZB natural capital assessment framework. Finally, the policy identifies a fair distribution for the costs and benefits of building net zero among all stakeholders. Rather than imposing all costs on the builder, local government, or the occupant, the policy aims to allocate costs and benefits justly among all stakeholders. To do so, the policy requires a preliminary set of inputs for the proposed building, as shown in Table 5-5.

Table 5-5. Preliminary data for policy analysis

Building Type	Residential, commercial, industrial, institutional
Builder Type	Public, private, P3
Occupant Type	Public, private, mixed-use
Building Location	Availability of natural capital
Building Size	
Number of Building Occupants	Full Time Equivalent (FTE)

5.2.2 Net Zero Natural Capital Assessment

The NZB policy is based on the NZB natural capital assessment framework developed in Chapter 3. The framework is used to evaluate the life cycle economic and environmental cost of a NZB.

In this step, the objective is to identify the environmental impact of the building designed to meet only the National Building Code of Canada and the provincial building code (BC Building Code) requirements. Then natural capital assessment is conducted to evaluate how the building can reach the net zero target. The effort (cost) of improving the building from code-minimum to net zero will be fairly distributed among stakeholders.

A demand assessment is performed to evaluate the building's energy and water needs, and their environmental footprint in terms of CO_2 equivalent. A life cycle assessment (LCA) is performed to estimate the building's emissions in terms of CO_2 equivalent. Then, outputs of these systems are integrated to identify total impacts of the building that is designed to code-minimum.

Natural capital assessment is then conducted for three modules: energy, water, and building materials. The goal of this step is to evaluate how the building can achieve the net zero target. The natural capital available for use in buildings varies according to location of the buildings. Table 5-6 lists the main parameters of natural capital related to sustainable building systems.

Table 5-6. Main parameters of natural capital for buildings

Building System	Parameters
Energy	Wind energy Solar energy Geothermal energy
Water	Precipitation Groundwater
Building Materials	Rapidly renewable materials

A NZB Index in this methodology is defined as 'a building with net zero CO_2e emission throughout its life cycle,' as shown in Eq. 5-1:

$$Net\ Zero\ Building\ Index\ (NZI) = \sum_{t=0\ (cradle)}^{t=T\ (grave)} E_{CO_2e} + W_{CO_2e} + M_{CO_2e} \ \textbf{[Eq. 5-1]}$$

Where:

E is net-emission due to energy use

M is net-emission due to materials use

W is net-emission due to water use

T is building life span

In addition to an environmental assessment using natural capital for NZBs, the economic benefits of the building are evaluated by conducting a LCC assessment as described in section 3.8.

The results of the natural capital assessment and LCC analysis identify the amount of environmental improvement and associated cost that a building designed to code-minimum requires to reach net zero. This cost will be spread among the building stakeholders using a game theory approach as described in the following section.

5.2.3 Cost Benefit Distribution Among Stakeholders

The NZB policy aims to enforce NZB construction without putting all of the burdens on one stakeholder. Considering that environmental challenges such as global warming are global issues, all stakeholders will benefit from net zero construction. Government regulations and policies have been the main driver of net zero construction across the world. Adopting this policy leads to market transformation toward net zero carbon construction, as all builders are required to obey.

The developed policy allows distribution of NZB costs among multiple stakeholders based on building parameters. Multi-stakeholder systems are situations where two or more agents interact. The stakeholders engage in a negotiation to share the cost of NZB. Game theory is used to model the negotiation and possible outcomes.

Game theory, in its current form, was developed by John Nash (1950) based on a mathematical foundation that was created by Von Neumann and Morgenstern (1944). Game theory classifies models for states of players and offers various solutions for each model. Solutions are the outcomes that may occur in the game. The game is a representation of interactions between stakeholders and shows all of the possible actions each stakeholder can play. It also shows how much interest they have in each action, but not the actions they do play. For an in-depth review of game theory, refer to Leyton-Brown and Shoham (2008). Game theory models can be categorized into four groups (Osborne & Rubinstein, 1994):

- Strategic and Bayesian games
- Coalitional games
- Extensive games with perfect information
- Extensive games with imperfect information

The stakeholders' interactions can be modeled either as competition (their desires confront) or as coalition if their desires coincide. Game theory is a natural and effective method to model multi-stakeholder situations where outcome depends on all stakeholders' decisions (Nagarajan & Sošić, 2008). Game theory has been used for fair distribution of costs and benefits among stakeholders to stabilize environmental decisions (Soltani, 2015). Kaitala and Pohjola (1995) used game theory to study climate change in the framework of an environmental negotiation problem. Soltani et al. (2016) used game theory to find a sustainable solution among multi-stakeholders for municipal solid waste treatment. Weikard and Dellink (2008) studied renegotiations of international climate agreements by using game theory.

Even though individual stakeholders are inclined to choose an option that maximizes their benefits, game theory seeks solutions that are stable in a mutual setting. In such a setting, stakeholders' decisions are based on a series of 'what if' questions. These questions are set to evaluate stakeholders' reactions to each other's decisions. The questions ask whether the stakeholder would change their initial decision if the other stakeholder selects any of the possible options.

Among the many solutions available for game theory, Nash equilibrium is the most common solution (Soltani et al., 2016). Nash equilibrium is based on the Pareto efficiency (or Pareto optimality) concept in which improvement in the state of one stakeholder is only possible if another stakeholder's state declines.

Strategic games are useful to model negotiation over environmental issues where stakeholders have competition and need to reach decisions directly (Soltani et al., 2016). The NZB policy can be defined as a strategic game, in which negotiation occurs between the builder and local government when the builder applies to obtain a permit for construction. If the building occupant is known at that stage (in case of public buildings), the building occupant can be part of a secondary negotiation with the builder. In all cases, it is assumed that the local government's duty is to consider the building occupants' interest in the negotiations. Therefore, it is assumed that negotiations are a 'two-player' game. Since more than one stakeholder is affecting the distribution of costs and benefits of NZBs, an optimal option for each stakeholder cannot be reached. The actions of all stakeholders impact the optimal decision (Shoham & Leyton-Brown, 2008).

A game is created from the following elements (Osborne & Rubinstein, 1994):

- A ($a_1, \dots, a_i$) is a set of actions available to each stakeholder
- C ($c_1, \dots, c_i$) is a set of possible consequences for the actions in A
- g: A $\rightarrow$ C is a consequence function that links each action to a consequence
- $\geq$ is a preference relation defined on the set C;
- U: C $\rightarrow$ R is a utility function, a specific preference relation with the condition of $x \geq y$ if $U(x) \geq U(y)$. Utility functions are used to show preferences of each stakeholder.

In the net zero policy, these elements are defined as follows:

- A is a set of strategies that can help a building reach a net zero target.
- C is the set of net zero index (Eq. 3-12) and NPV (Eq. 3-13) that shows the outcome of selecting and implementing each set of net zero strategies (A) for each stakeholder. In other words, C shows the portion of cost that each stakeholder will be responsible for in each selected option in A.
- Lower net zero index is more preferable to each stakeholder.
- g: is a consequence function that links each action from A to a consequence from C.
- Utility function is the net zero index. If net zero strategy a_1 is preferred over a_2, then NZI (a_1) < NZI (a_2).

The first step of a two-player game is to collect information on stakeholders' utilities (benefits) from each pair of actions. The objective of this step is to identify how much stakeholder *1* benefits if stakeholder 1 chooses action *a* and stakeholder *2* chooses action *b*. This information forms a strategic game table as shown in Table 5-7. In the table:

- Each vector $a = (a_1, \dots, a_n) \in A$ is an action profile available to stakeholder i
- NZIi : $A \rightarrow R$ is the net zero index function representing the utility function for player i (u_i)

Table 5-7 Strategic game with 2 players and 3 actions

Stakeholders	Stakeholder 2 (Builder)			
Stakeholder 1 (Local government)	**Actions**	**a_1**	**a_2**	**a_3**
	a_1	NZI_{11}, NZI_{21}	NZI_{11}, NZI_{22}	NZI_{11}, NZI_{23}
	a_2	NZI_{12}, NZI_{21}	NZI_{12}, NZI_{22}	NZI_{12}, NZI_{23}
	a_3	NZI_{13}, NZI_{21}	NZI_{13}, NZI_{22}	NZI_{13}, NZI_{23}

NZI (a_1) is calculated as $\sum_{t=0\ (cradle)}^{t=T\ (grave)} E_{CO_2e} + W_{CO_2e} + M_{CO_2e}$

Where:

E is net-emission due to energy use, based on Eq. 3-4

M is net-emission due to materials use based on Section 3.5

W is net-emission due to water use on Eq. 3-9

T is building life span

As noted previously, Nash equilibrium can be used to find a solution to the game identified in Table 5-7. There is at least one Nash equilibrium for every game with a finite number of players and action profiles (Nash, 1951). Nash equilibrium is reached when both stakeholders classify an action set as a preferred option.

Following are the NZB strategies (A) that are available to stakeholders. Using game theory, the utility function of each option for each stakeholder is calculated and then, using Nash equilibrium, the preferred option is selected. The preference of each option based on type of builder and type of occupant (public versus private) is identified. The cost of each NZB strategy (A) is calculated using Equation 5-2:

$$C_{NZB}: C \subseteq (0, \infty), (C_{NZB} > NZI_1 - NZI_S) \cup (C_{NZB} > NZI_2 - NZI_1) \qquad [Eq. 5\text{-}2]$$

Where:

C_{NZB} is the cost of NZB strategy

NZI_1 is the NZI of option 1 for stakeholder 1 (local government)

NZI_2 is the NZI of option 1 for stakeholder 2 (builder)

NZI_S is the NZI of the selected option

5.2.3.1 Green Incentives

Government incentives are one of the ways to share the cost of building net zero. Local, provincial, or federal governments have budgets for environmental protection and can allocate a portion of this fund for NZBs. This method has been used among leading countries in sustainable development, such as Norway (Nykamp, 2016). Green incentives can cover a portion of the improvement costs necessary to bring the building to net zero carbon. Analysis conducted in Section 5.1 showed that performance of NZBs depends largely on the behaviour of building occupants. Green incentives can be used to educate building users, which will result in better sustainability performance of the building.

Incentives can be sub-categorized into two groups. The first type is direct incentives where government provides monetary value to the builder to cover a portion of net zero update costs. The second type is indirect incentives where government provides monetary-equivalent benefits to the builder. The indirect incentives can include allowing a higher Floor Space Ratio (FSR) for the NZB. Therefore, the builder has more floor area to sell and generate money. Another indirect incentive is providing access to reserved natural capital, such as groundwater, or renewable building materials such as wood. Green incentives are effective for both private and public builders and occupants.

5.2.3.2 Sustainable Building Tax and Renewable Energy Grid

Sustainable building taxation and renewable energy market are an effective solution for public buildings and private buildings where the builder keeps the building ownership throughout the building life span. In this option, the builder has invested in renewable energy and closed loop water systems and will benefit from energy and water cost savings during the operational phase. The builder can generate money to offset their initial natural capital investment in two forms. The builder can impose a sustainable building tax to building occupants since the occupants' energy and water costs are covered. Analysis conducted in Section 5-1 showed that LCC and payback period is most sensitive to interest rates and cost of energy and water from the grid in that region.

Also, a building can generate more energy and capture more water than it needs for its operation. The excess energy and water can be sold back to the grid at a predefined price. This is an effective and established method and currently the City of Toronto (2017) in Canada has a program for purchasing excess renewable energy that buildings generate.

5.2.3.3 Offsite Natural Capital Investment and Carbon Taxation

To achieve the net zero target, a building's energy and water systems should be designed with higher efficiency so the building consumes less energy and water over its life span. Also, the building needs to generate renewable energy to offset the energy it uses and capture its water demand. This renewable energy generation and water management can be on-site or off-site. On-site renewable energy generation occurs within the building site area, from solar, wind, or geothermal energy sources. In on-site water management, a building captures its needed water from precipitation and groundwater sources.

If a building does not have enough space to generate its needed energy or capture its needed water on-site, the builder can invest in off-site natural capital to offset the amount of energy and water that building receives from the grid. Natural capital analysis conducted in Chapter 4 for the LBC building showed that the building does not have enough capacity to generate all of its energy demand on site. Therefore, the building should rely on an off-site natural capital investment to offset non-renewable energy that it receives from the grid. Off-site natural capital investment can include investment in renewable energy generation or investing in cisterns to capture water in another location.

The local government can also impose carbon taxation for the amount of carbon that the building cannot offset. This option is most suitable for private, small-scale buildings where the building location does not have access to enough natural capital.

5.3 Summary

Sustainability assessments for buildings are usually conducted at early stages of the design of the building. At this stage, much of the data that influences the assessment are unknown, vague, or uncertain. Therefore, it is essential to include uncertainty in the sustainability assessment. Current NZB rating systems do not consider uncertainty as part of their assessment. The sustainability assessment is based on deterministic data. In this chapter, sources of uncertainty were identified and different types of uncertainty, including parameter, model, and scenario were discussed. An uncertainty assessment was then performed for the NZB Framework. The result of the assessment shows that the parameters related to user behaviour during the operational phase of the building are less certain and are based on less reliable information. These parameters include energy consumption of plug load during the operation of the building, and indoor water consumption. Uncertainty analysis shows that if building occupants consume water more than the intended design, it could increase the total emissions of the building significantly to 1771.6 tonnes of CO_2e.

Uncertainties in the LCA, LCC, and natural capital models were discussed. Results of the LCA analysis show that using different LCI databases results in a 7.5% variation in the CO_2e emission. The LCC assessment is highly sensitive to the discount rate (i) and life span of the building. The longer the building is operational, the higher the financial benefits.

In addition, various scenarios for the end-of-life use of building materials were investigated. End-of-life of building materials is a key cause of uncertainty in NZB assessments because often there is little or no information available on the end-use of the building while assessing for net zero. The result of the assessment shows that reusing and recycling building materials could reduce building emissions by 50%.

Based on the results of the uncertainty assessment, sustainability assessments are most sensitive to building life span, building occupant (user) behavior, and end-of-life scenarios for building materials. Educating building occupants about the sustainability goals of the building is a crucial part of achieving the sustainability target. However, green building education is usually the broken link in the chain of sustainability and one of the main reasons why many 'sustainable' buildings do not perform as intended. It is important to consider continuous Measurement and Verification for the building energy and water systems during the operational phase and monitor the actual consumption of these resources versus their intended design.

In the second part, based on the developed framework for NZBs, some policy recommendations were made. These recommendations will guide a fair distribution of life cycle costs and benefits of NZ buildings among all building stakeholders. NZBs are used globally as a main government strategy for addressing climate change. However, there are only a limited number of NZBs in the province of British Columbia due to a lack of a comprehensive net zero policy in the Province.

Chapter 6. Conclusions and Recommendations

6.1 Summary and Conclusions

The building and construction industry is accountable for a significant portion of the environmental challenges that our generation faces. Therefore, there is a need for a paradigm shift from traditional construction practices toward sustainable development. The NZB is a viable solution to address this challenge. Many countries around the globe, including the United States, the European Union, and China have realized this fact and are setting goals to achieve net zero targets in buildings.

Even though design and operation of NZBs are closely linked to their surrounding environment, existing NZB rating systems and frameworks do not consider local natural resources in their assessment of buildings. Despite the significance of geographical characteristics and local environmental conditions, consideration of regional resources in green buildings is largely lacking in the literature.

This research study attempted to fill the knowledge gap by developing a framework for assessment of local natural capital to achieve net zero targets in buildings. The framework considers the full life cycle of buildings and evaluates how the building can become self-sufficient with net zero impact by effectively using local natural resources. Energy, water, and building materials are selected as the three main components of NZBs.

Chapter 1 provided a background to sustainable buildings, identified the research gap, and identified objectives of this research study. Chapter 2 provided a comprehensive literature review on various sustainable building types, including green buildings, near zero buildings, and NZBs. Then strengths and limitations of existing sustainable building assessment frameworks were discussed. This chapter also provided a literature review on natural capital assessment and main drivers of sustainable buildings around the world.

The research methodology was developed and discussed in Chapter 3. The methodology developed in this chapter used natural capital to evaluate net zero targets in buildings.

The methodology framework consists of four main steps. At the first step, a system boundary for the building is defined, and related building data that are required in the framework are collected. Then, a demand assessment is performed for each of the main components of the building. At the next step, the building location is analyzed and a natural capital assessment is conducted for three modules: energy system, water system, and building materials. The outputs of these steps are fed to the systems integration module to identify the building's environmental footprint. A decision support tool is then used to identify how the building can become net zero carbon over its life cycle. Finally, an economic assessment is performed to evaluate the cost-effectiveness of the building. The methodology aimed to provide a decision support tool to building stakeholders and evaluate sustainability options to implement in the building's design.

In Chapter 4, the methodology was applied to an LBC building to evaluate whether the building is net zero over its life cycle. Contributions of each of the building components were investigated and various scenarios for getting the building to net zero were analyzed. The result indicated that the LBC design is not net zero CO_2e over the life of the building. Building materials demonstrated the highest CO_2e emission impact (69%) over the life of the building, but the embodied impact of building materials is not considered in LBC. Various scenarios were considered to bring the building to net zero CO_2e emission over its life cycle. The result showed that the building could become net zero CO_2e emission over its full life cycle by investing more in renewable energy and employing materials recycling and an off-site carbon offset program. The building could generate 100% of its energy from renewable energy sources. Among the renewable energy sources, solar and geothermal have the highest energy generation potential for the building's location. Besides energy, the building could capture 92% of its water needs on site from precipitation and groundwater.

Chapter 5 consists of two parts. In the first part, a detailed uncertainty analysis was performed, sources of uncertainty were identified, and different types of uncertainty, including parameter, model, and scenario, are investigated. Based on the result of the uncertainty assessment, the sustainability assessment is most sensitive to building life span, building occupant (user) behavior, and end-of-life scenarios for the building materials. Educating building occupants about the sustainability goals of the building is a crucial part of achieving the sustainability target.

In the second part of Chapter 5, NZB policy suggestions were provided based on the developed NZB assessment framework and the uncertainty analysis results of Section 5.1. The policy aims to provide a fair distribution of life cycle costs and benefits of NZB among all building stakeholders. Three strategies were discussed for allocation of cost and benefits, namely, green incentives, sustainable building tax, and off-site natural capital investment.

6.2 Originality and Contributions

Previous studies of NZBs acknowledged the importance of considering full life cycle and local resources but did not include these in the assessment framework. Although design, construction, and operation of buildings are in direct relation to the surrounding environment, regional characteristics are inadequately considered in net zero assessment frameworks. The main academic contribution of this research is to close this gap by developing a natural capital-based assessment framework that provides location-specific solutions to achieve net zero target in buildings. There has been no comprehensive decision support system or framework for NZBs that provides location-specific solutions to achieve net zero targets. Also, the developed framework covers the entire life cycle of buildings. Existing NZB rating systems, such as Living Building Challenge, only cover partial life of buildings (construction plus 1 year post-occupancy).

In addition, this research is based on an original idea of integrating building modules, so that deficiencies in one module can be covered by another. The energy, water, and building material modules are impact-based and integrated, so the end results are represented in a single metric (CO_2 equivalent). This method leads to unbiased, multi-criteria decision making, while existing sustainable building rating systems (such as LEED and LBC) are consensus based.

The contribution of this research is to assist stakeholders in assessment and decision making related to NZBs at the pre-design stage of the building. In other words, this research tries to answer all three main questions of sustainable buildings: What is a NZB? Why are NZBs beneficial? and How can these net zero targets be achieved considering the geographical location and characteristics of the building?

NZB policy recommendations in this thesis provide a method for fair distribution of costs and benefits of NZBs among all stakeholders. The NZB policy can assist building stakeholders in their negotiations and can accelerate the decision-making process.

6.3 Applications

The developed NZB assessment framework allows building stakeholders to evaluate natural resources in their region and assess life cycle costs associated with NZBs. The framework helps stakeholders to explore sustainable strategies that can lead to achieving net zero impact. The presented framework aims to create a dialogue among academic researchers in the field of sustainable built-environment on the significance of natural capital in research and development of future buildings. Moreover, the developed framework provides policy suggestions for NZBs based on fair allocation of costs and benefits among all involved stakeholders. This process will avoid free riding, where one stakeholder carries all costs associated with construction of NZBs but multiple stakeholders benefit. The policy suggestions can help local governments, builders, and the public to negotiate for reasonable distribution of fees and profits. This framework directly promotes sustainable development in Canada by outlining benefits of sustainable construction, developing a robust framework to assess NZBs, and providing policy suggestions for regions where a sustainable construction policy is not available.

6.4 Limitations and Recommendations

The following limitations were observed in this study and some recommendations are provided for the future steps of research:

- The framework only considers the top three building systems (energy, water, and building materials) for net zero assessment. Other building systems such as information and data could be considered.

- The scope of net zero is limited to net zero carbon emissions. Other environmental impacts such as soil erosion, acidification, smog, and human health could be considered.
- The scope of sustainability assessments is limited to environmental and economic factors (LCA and LCC); social impacts are often ignored in green building assessments. Including social sustainability parameters, such as affordability, diversity, land use, safety, and proximity to other services, could improve the quality of the assessment.
- Energy and water assessments of buildings are based on design data and not actual use. Energy and water use during the operation of the building should be measured. The data used in preliminary energy and water assessment should be verified and updated if necessary.
- Hydropower, biomass, and tidal energy are excluded from the renewable energy choices for small-scale buildings. With further research advancements, these renewable energy sources might become viable in the future and could be added to the framework.
- The LCA was conducted using the Athena Impact Estimator for Buildings. The life cycle inventory (LCI) of this software includes only 95% of the building materials used in the North America. For products whose LCA data is not available in Athena LCI, other databases such as Ecoinvent could be considered. If data is not available in LCIs, an LCA should be conducted for the product using the ISO 14041 method.
- Uncertainty analyses for unchecked scenarios including climate change, geopolitical scenarios, variation in emission Conversion Factors (CFs), were not completed due to lack of data. Appropriate data could be collected to create models for these scenarios.
- In the study, reasonable assumptions were made for missing data. Using actual data is recommended for future research.

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Appendix A – Regional Analysis of LEED Projects in Canada

To study the relationship between the location of green buildings and regional resources, 100 LEED buildings across Canada that received certification under one of the LEED Canada (CaGBC, 2016) version 2009 rating systems are studied. The rating systems include LEED for New Construction and Major Renovations, LEED for Core and Shell Development, and LEED for Retail. The building and certification data were collected from the CaGBC project profile database (2014) and USGBC LEED project directory (2014). ArcGIS software is used for analysis and presentation of data. Figure A-1 shows the location of these LEED certified buildings on a map.

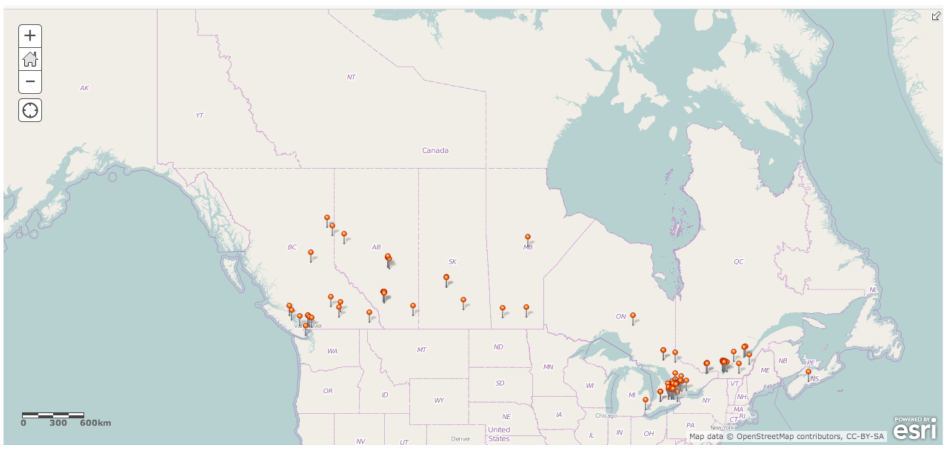

Figure A-1 Location of LEED certified buildings in Canada

- **Trend of energy saving in green buildings across Canada**

Energy saving is one of the most important parameters of sustainability in the built environment. Figure A-2 shows the number of points awarded to each building for energy performance (LEED credit EAc1 Optimized Energy Performance).

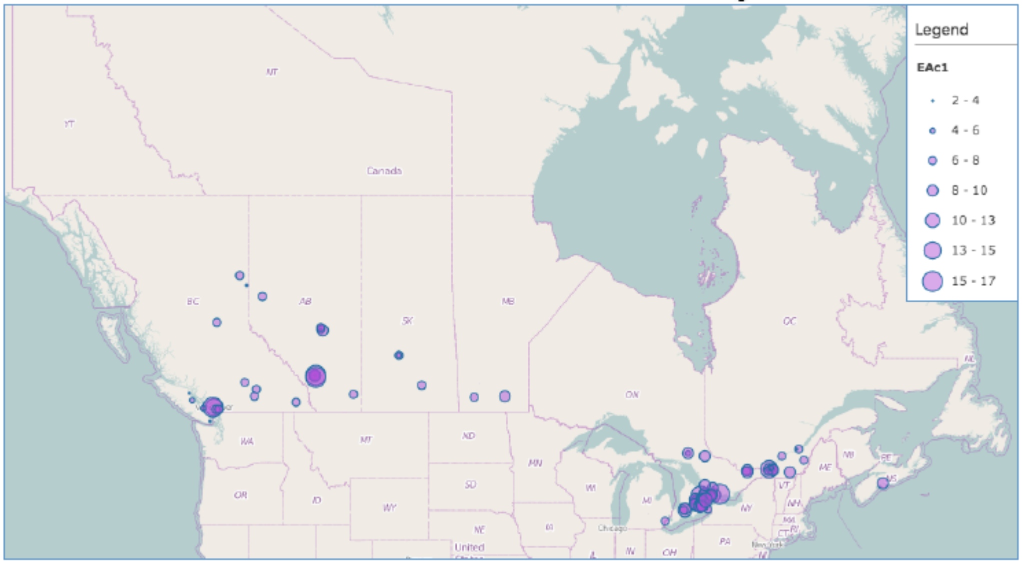

Figure A-2 Energy saving in green buildings across Canada

These points are calculated based on energy savings compared to the building energy standard defined by ASHRAE 90.1 (2007). Table A.1 shows energy points based on percentage of energy saving.

Table A-1 Energy points based on energy saving

Points	Energy Saving	Points	Energy Saving	Points	Energy Saving
1	12%	8	26%	14	40%
2	14%	9	28%	16	42%
3	16%	10	30%	17	44%
4	18%	11	32%	18	46%
5	20%	12	34%	19	48%
6	22%	13	36%	20	50%
7	24%	14	38%		

On average, projects in the provinces of Alberta and Ontario have the highest energy savings in Canada with 28%, followed by buildings in British Columbia with 24% and in Quebec with 22% energy use reduction. The regional analysis shows that buildings in suburban and rural areas have less energy savings compared to green buildings in developed urban areas. This is mainly due to a lack of green building policy in these regions (Discussed further in Chapter 5).

On-site renewable energy generation (LEED credit EAc2) and investment in off-site renewable energy generation (LEED credit EAc6) are among the key strategies to reduce the environmental impacts of buildings that rely on grid sources for their energy supply. Figure A-3 illustrates the location of buildings that have implemented these strategies.

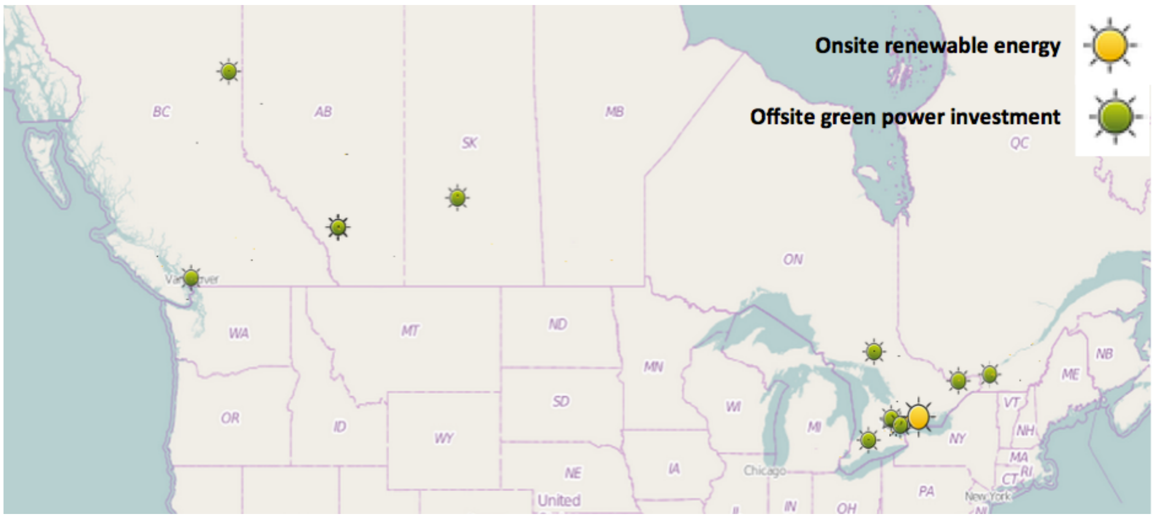

Figure A-3 On-site energy generation and off-site energy investment

Even though most of regions of Canada have a high photovoltaic potential (kWh/kW) of 1000 to 1400 (NRC, 2014), only 2% of green buildings use on-site renewable energy and only 15% of buildings across Canada (mainly in the metro Toronto region) invest in off-site renewable power generation from wind and solar.

- **Building water use reduction across Canada**

Water is a precious resource used in buildings. The number of points achieved by buildings for outdoor water savings due to efficient landscaping (LEED credit WEc1) and indoor water use reduction (LEED credit WEc2 and WEc3) are shown in Figure A-4.

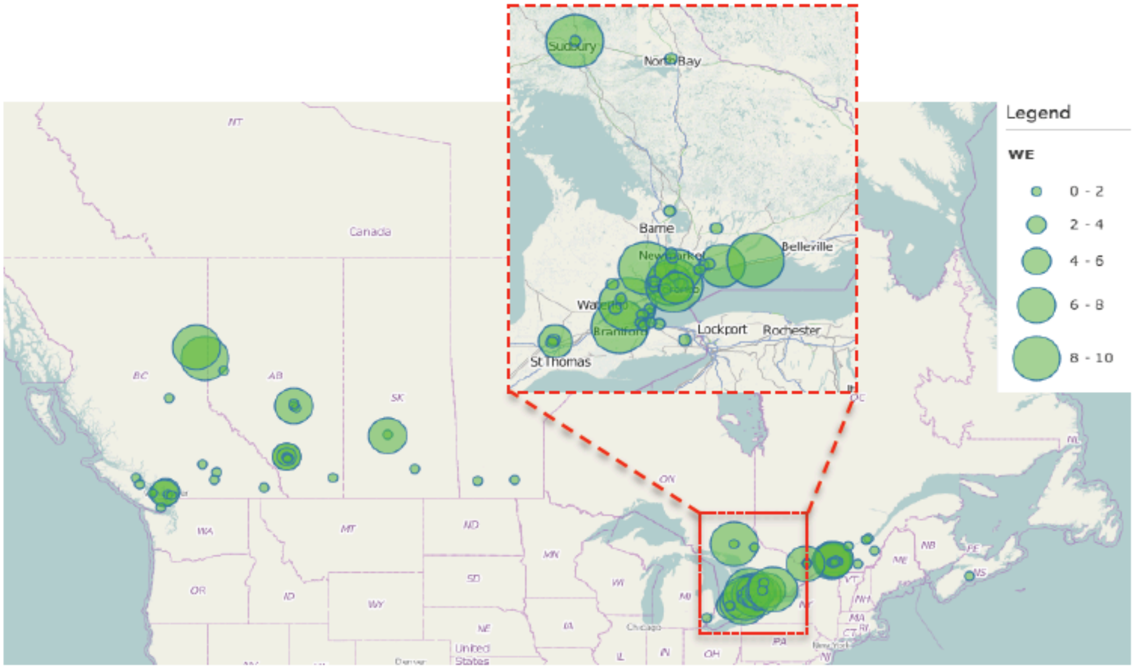

Figure A-4 Building water use across Canada

Analysis of this study shows that on average, LEED certified buildings in Canada have 30% water savings compared to conventional buildings. Interior regions in the provinces of British Columbia, Alberta, Manitoba, and Saskatchewan, with 100-200 mm of mean annual precipitation, have the lowest amount of precipitation in Canada and water conservation should be more stringent in these regions. However, the spatial analysis shows that LEED certified projects in these regions have the least amount of water savings. The highest amount of water saving in buildings occurs in southern Ontario, which also receives one of the highest amounts of precipitation in Canada (800-1200mm) (Atlas of Canada, 2009).

- **Sustainable materials and construction waste reduction across Canada**

Considering that buildings consume 30-40% of the limited natural reserves on the planet (Roodman & Lenssen, 1995), using sustainable materials and construction waste reduction is of key importance in green buildings. Figure A-5 shows the number of points awarded by LEED projects in the Materials and Resources (MR) category.

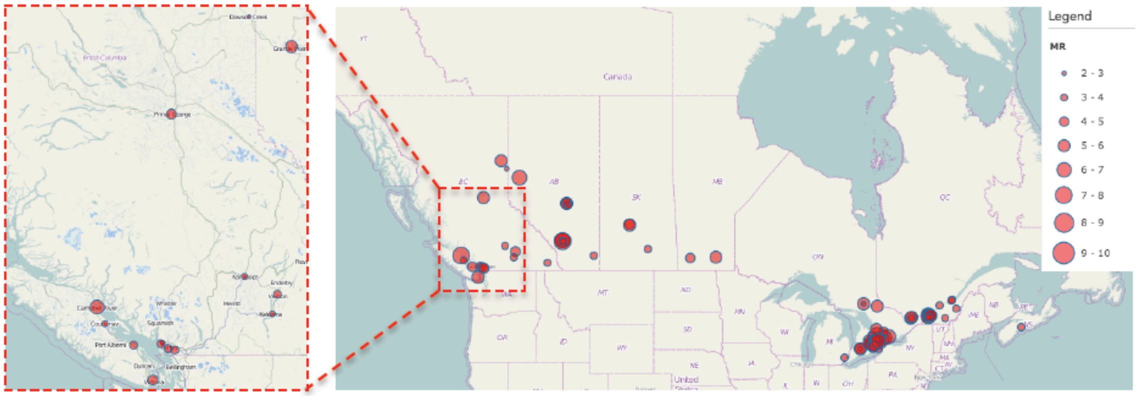

Figure A-5 Sustainable materials and construction waste reduction across Canada

Buildings in BC have more than a 50% diversion rate for construction waste. It is an important achievement noting that more than half of land-filled generated waste comes from construction and building activities (USGBC, 2007). However, regional building materials and materials with recycled contents are not widely used in buildings across Canada.

Regional analysis shows that Canada has rich natural capital resources that can be used strategically to reduce the impacts of buildings. However, sustainable buildings do not take full advantage of these resources and are not designed based on the needs of their regions.