Analysis of NetZero Energy Homes (NZEHs): Stakeholders, Design, and Performance

by

Hong Xian Li

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Department of Civil and Environmental Engineering
University of Alberta

Abstract

NetZero Energy Homes (NZEHs) have emerged as a promising solution able to alleviate the energy strain that residential buildings exert on limited natural resources, thereby reducing the detrimental impact on the environment. Since the Government of Canada announced the NetZero energy healthy housing initiative in 2005, and the NetZero energy home coalition fostered the long-term vision that all new homes be built to net zero energy standards by 2030, many efforts have been made to realize this ambitious goal. Meaningful progress has been made in this regard; however, there still exist outstanding questions that must be answered: after the residential housing industry invests in the development of NZEHs, are customers willing to buy? What are the impacts of NZEHs on stakeholders? Based on the state of the art, how can NZEH design be improved? What are the effective means to improve the actual performance of NZEHs?

In response to these important questions, this research is developed to achieve the following objectives: (1) to identify market acceptance and impacts on stakeholders of NZEHs through stakeholder analysis; (2) to investigate energy performance of design scenarios through energy simulation; (3) to assess and analyze the actual energy performance of NZEHs, based on sensor data collected using continuous monitoring; and (4) to conduct energy calibration and cost analysis in order to improve NZEH design by integrating the energy simulation, energy monitoring, and survey results. The holistic knowledge gained through the study and analysis can be employed to promote NZEHs, and to improve the design and operation of NZEHs.

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Abbreviations

CDDs: cooling degree days

CMHC: Canada Mortgage and Housing Corporation

CT: current transformer

CWC: Canadian Wood Council

DHW: domestic hot water

DOE: U.S. Department of Energy

ERV: energy recovery ventilator

EPS: expanded polystyrene

FiTs: feed-in tariffs

HDDs: heating degree days

HRV: heat recovery ventilator

HVAC: heating, ventilation, and air conditioning

MSE: Mean-squared error

NEB: National Energy Board of Canada

NSERC: Natural Sciences and Engineering Research Council of Canada

NZEB: NetZero energy building

NZEH: NetZero energy home

Solar PV: solar photovoltaic

SPF: spray polyurethane foam

XPS: extruded polystyrene

Chapter 1 Introduction

1.1 Background and Motivation

Energy consumption is a crucial issue which has garnered world-wide attention, particularly in cold-climate regions such as Canada. The National Energy Board of Canada (NEB) (2013) analyzed energy consumption by sector in Canada in 2011, which resulted in the following findings: (1) energy use in the residential sector, including for space heating and cooling, hot water heating, lighting, appliances, and other energy-using devices, accounts for 14% of the country's total energy consumption, and the energy demand will increase at an average annual rate of 0.7% between 2011 and 2035; (2) the commercial sector, which includes office, retail, warehouse, government, and institutional buildings, contributes 13%; (3) the industrial sector, including manufacturing, construction, mining, agriculture, forestry, and fisheries, represents 48%; (4) the transportation sector, including passenger and freight on-road transportation, as well as air, rail, marine, and non-industrial off-road travel, accounts for 21%. In the United States, it has been reported that the construction sector and the building operation combined account for 39% of energy use (United States Green Building Council 2009). For the purpose of reducing the energy usage of construction and buildings, various measures have been taken, including energy-efficient building design, optimized material selection, and environmentally-friendly construction processes. As a result, the concept of NetZero Energy Homes (NZEHs) has emerged as a promising solution.

Referring to the common definition for a zero energy building by the U.S. Department of Energy (DOE) (2015), a NetZero Energy Home (NZEH) is defined in this research as a home which produces enough renewable energy to meet its own annual energy consumption requirements, thereby reducing the use of non-renewable energy in the residential building sector. Efforts have been made around the world to promote the development and marketing of NZEHs. The Net-Zero Energy Home Coalition, which is a multi-stakeholder group in North America, supports the long-term vision that all new homes in Canada will be built to be net-zero energy by 2030 (Government of Canada 2005). The Government of Canada (2005) also announced the NetZero energy healthy housing initiative for the purpose of advancing the objective of achieving net-zero energy for new Canadian housing, which has been officially branded EQuilibrium™ Housing, and is led by the Canada Mortgage and Housing Corporation (CMHC) as a national initiative to demonstrate the potential of sustainable housing. To achieve this ambitious goal, concerted efforts also have been made by such stakeholders as authorities, residential builders, and the solar energy industry, but a number of questions remain to be answered. After all the efforts made by these stakeholders, will the NZEHs be accepted by the residential market and customers? What are the impacts of this new NZEH concept on the stakeholders? Furthermore, is the current state of the art being taken into account in order to optimize NZEH design decisions? How are NZEHs actually performing, and how can NZEH design be improved incorporating the actual performance and also incurring the least initial cost?

In order to answer these questions, the aim of this research is to ascertain the extent of market acceptance of NZEHs and the impacts of NZEHs on stakeholders, assess the performance of NZEHs, and improve NZEH design. This research is based on a Collaborative Research and Development (CRD) project sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Landmark Group of Companies (Landmark), an Alberta-based homebuilder and one of the leaders in the development of NZEHs in Alberta.

1.2 Research Objective and Framework

1.2.1 Research Hypothesis

This research is built on the basis of the following hypothesis:

Holistic knowledge gained through stakeholder analysis to identify market acceptance and impacts on stakeholders, energy simulation to investigate energy performance of design options, energy monitoring and analysis to assess actual performance, and a two-step cost analysis based on energy calibration can be applied to improve NZEH design and to promote NZEHs.

1.2.2 Research Objectives

This research aims to identify holistic knowledge pertaining to NZEHs, including the market acceptance conditions, the impacts of NZEHs on stakeholders, the energy performance of the building envelope and mechanical system options, the actual performance, and optimal design for NZEHs. In order to achieve the research goal, the following detailed research objectives are pursued:

(1) Identify the market acceptance conditions and the impacts of NZEHs on stakeholders through stakeholder analysis;

(2) Investigate the energy performance of design options in order to support informed design decision, utilizing energy simulation as the approach;

(3) Monitor and assess the actual performance of NZEHs, with sensor technology employed;

(4) Improve NZEH design while reducing initial cost, based on energy calibration which incorporates the energy simulation, the monitored performance, and the energy performance acceptance of an NZEH.

1.2.3 Research Framework

The research framework is displayed in Fig. 1-1: (1) focus group and survey are applied for stakeholder analysis in order to investigate the market acceptance and the impacts of NZEHs on stakeholders. (2) Energy simulation is employed in order to simulate the energy performance of the building envelope and mechanical system options for NZEH design, and the simulation results are used for such analyses as energy modelling, factor ranking, and cost-effective design scenario analysis. In keeping with current practice for the building industry in Canada, HOT2000 is selected as the energy simulation tool, and, to enhance the simulation capability, the Batch Version of HOT2000 is utilized in this research. RetScreen is used to estimate the energy generation. (3) Sensor technology is utilized to monitor and assess the actual performance of NZEH cases, and the collected data is also used for energy modelling and calibration. (4) By incorporating the calibrated energy (from energy simulation and monitoring) and the energy performance acceptance (from stakeholder analysis), cost-effective design scenarios are analyzed for NZEHs. The information flow and internal relations among the three pillars, including stakeholder analysis, energy simulation, and energy monitoring, is demonstrated in Fig. 1-2. This research yields holistic knowledge pertaining to stakeholders, design, and actual performance of NZEHs, and can thus be employed to improve the design and operation of NZEHs, and to promote NZEHs.

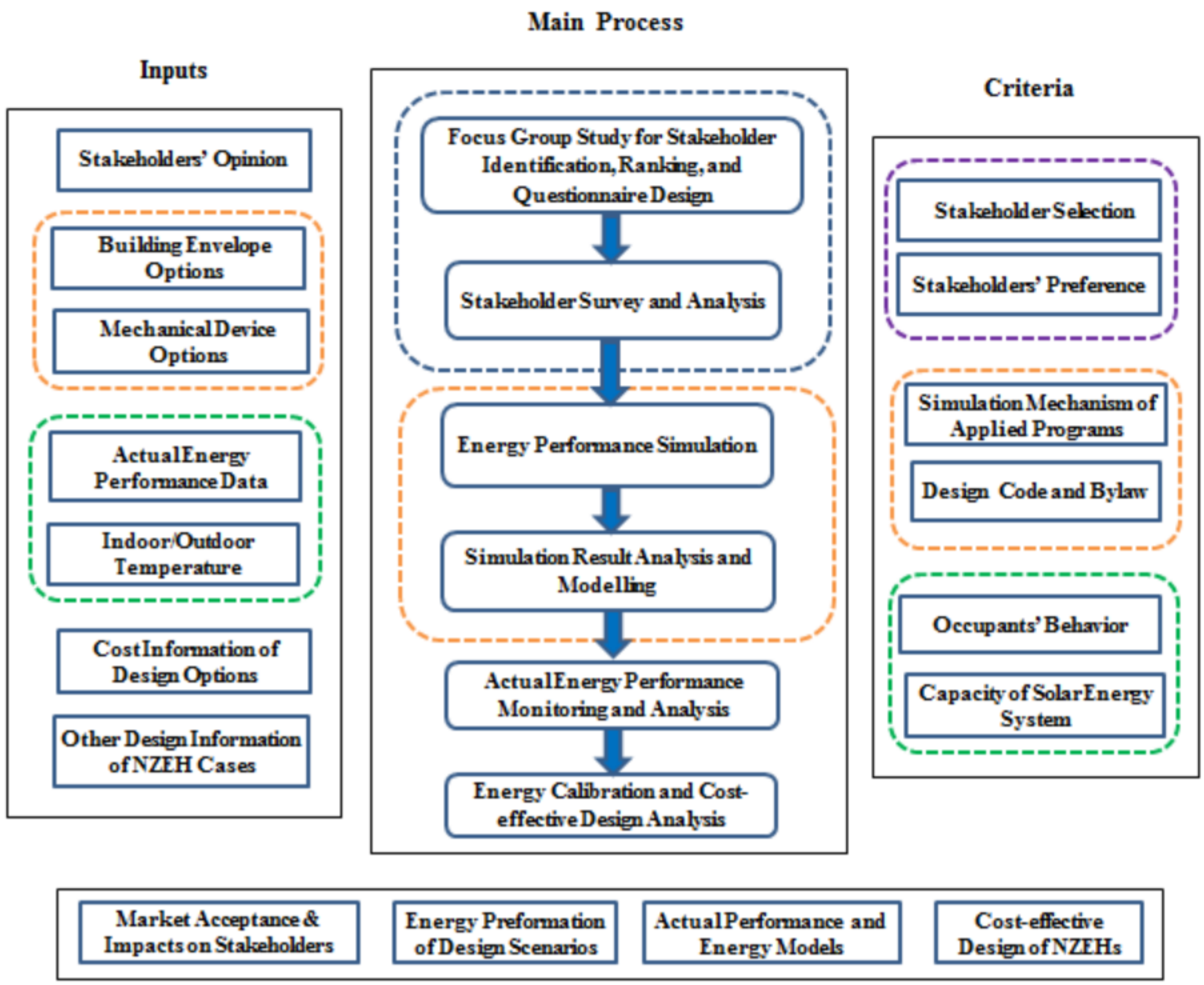


Fig. 1-1. Research Framework

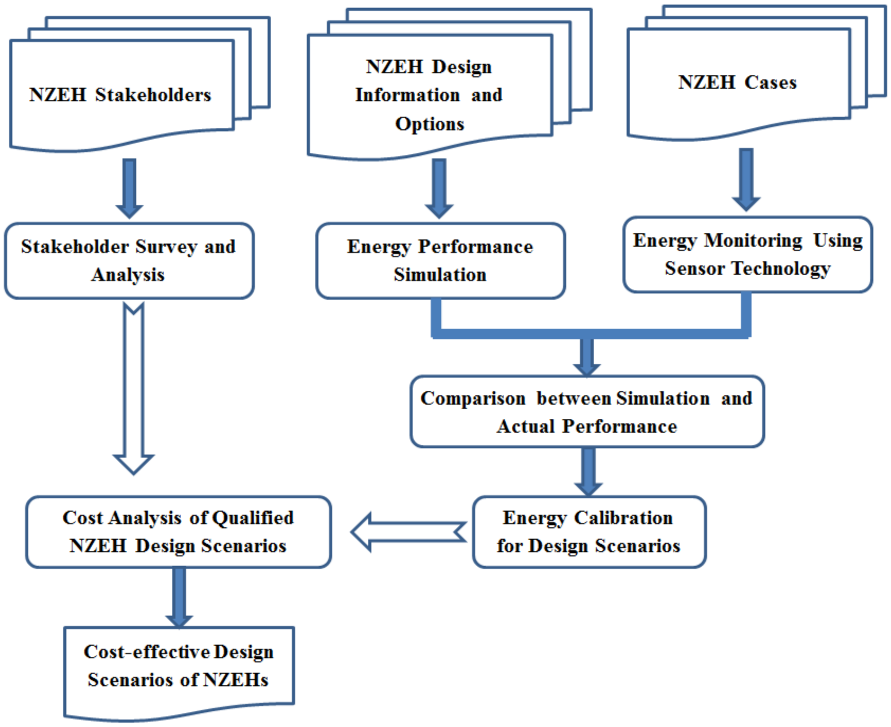


Fig. 1-2. Information Flowchart

1.3 Organization of the Thesis

This thesis comprises seven chapters. **Chapter 1** introduces the NZEH concept, and describes the research requirements to promote NZEHs based on the current state of the art. **Chapter 2** reviews the literature on stakeholder analysis, energy simulation, and energy monitoring and analysis. **Chapter 3** proposes a methodology with regard to stakeholder analysis and implementation for NZEHs. **Chapter 4** introduces a methodology for energy simulation, and demonstrates the implementation for NZEH design. **Chapter 5** proposes an energy monitoring and analysis framework for NZEHs. **Chapter 6** introduces a methodology to improve NZEH design through energy calibration and a two-step cost analysis. **Chapter 7** summarizes the research, and outlines the contributions and limitations, which can be mitigated in future work.

Chapter 2 Literature Review

2.1 NetZero Energy Building Initiatives

The detrimental environmental impacts of buildings and construction have gained worldwide attention, and have been studied from a lifecycle analysis (LCA) perspective (Blanchard and Reppe 1998; Bribian et al. 2009; Gustavsson and Joelsson 2010; and Dodoo et al. 2011). The overall LCA scope of a building, as summarized by Inui et al. (2011), includes: (1) extraction of raw materials; (2) transportation of raw materials to the material processing plant; (3) processing and manufacturing of composite items and building materials in the plant; (4) transportation of building materials to the site; (5) construction on site; (6) operation and maintenance; and (7) demolition, disposal, or recycle. Ochoa et al. (2005) have employed an estimating mapping method to conduct LCA for a wood-framed residential building in the United States. They have found that the total lifecycle energy consumed is 75.2 GJ/m^2, and the total CO_2 emissions are 3,010 kg/m^2. Junnila et al. (2006) have conducted LCA for two new steel-reinforced concrete office buildings in Europe and the United States, respectively. Their results show that the *operation phase* of the building in Europe accounts for 87% of the total energy used, while in the case of the United States the proportion is 83%.

Due to the fact that building operation consumes a tremendous share of total energy usage, energy efficient buildings are now being implemented in many regions around the world, and NZEHs are proposed as a novel solution for residential buildings. The NetZero Energy Building (NZEB) is a general term for net-zero energy buildings encompassing different building types. Numerous initiatives and programs have been taken to promote NZEBs around the world. Based on the U.S. DOE Builders Challenge program, hundreds of leading builders have been recognized for their achievements in energy efficiency since 2008 (DOE 2015). The Government of Canada led a NetZero energy healthy housing initiative to advance the objective of achieving net-zero energy consumption for new Canadian housing (Government of Canada 2005). The NetZero energy healthy housing initiative has been officially branded EQuilibrium™ Housing, and is led by CMHC as a national initiative to demonstrate the potential of sustainable housing (CMHC 2006). The European Parliament and the Council of the Europe Union (EU) adopted the recast of the energy Performance of Buildings Directive, which stipulates that new buildings in the EU will have to consume nearly zero energy by the end of 2020 (Europe Council for an Energy Efficient Economy 2010).

2.2 NZEB Evaluation and Promotion

NZEBs have been reviewed from perspectives of technology and performance worldwide. Musall et al. (2010) have conducted a comprehensive review of more than 280 NetZero Energy Buildings (NZEBs) in various countries throughout the world, resulting in the following information: (1) the distribution of NZEBs by country, where Canada accounted for approximately 30 of the 280 total buildings; (2) energy efficiency of three typology groups, "small residential building", "apartment building", and "non-residential building", for different building components; (3) on-site energy generating technology for three types of buildings, and comparison between primary energy credits and primary energy consumed. Based on reviews of six NZEBs (five in Canada and one in the United States), Proskiw (2010) has analyzed the best practices of design and construction of NZEBs in Canada, considering building envelope, mechanical system, and renewable energy system, and has proposed technology solution suites to support this new paradigm descriptively. Thomas and Duffy (2013) have investigated the performance of NZEBs in the New England region of the United States by using the information provided by the homeowners and utility bills, and the results have shown that, out of 10 NZEB cases, six attained at least net-zero energy, and the actual performance of NZEHs were found to be more dependent on occupant behaviour than on design.

Deng et al. (2014) conducted a comprehensive review outlining a method to evaluate NZEB performance from a lifecycle perspective, and summarized the typical evaluation process for NZEBs as follows: simulate the performance of NZEBs during design phase; after the construction of NZEBs, monitor the performance of NZEBs using sensor instrumentation, and validate the simulation model based on the collected data. Deng et al. (2014) also summarized the common evaluation indicators for NZEBs, including energy amount, system efficiency, and lifecycle assessment.

Overall industry strategies of improving performance and promoting market awareness/acceptance also have been proposed based on workshops. The NetZero Energy Home Coalition (2013) has hosted a workshop to identify the "path to zero", and summarized the priorities for five groups: policy & grid, driving market demand, finance & real estate, education & tools, and products & technologies. In order to achieve NZEHs, the National Institute of Standards and Technology (2013) has organized a workshop to identify and propose strategies for design, technology & equipment, home owners, and the building industry. Although the strategies have been proposed to promote NZEBs, the studies on stakeholder relationships and the impacts on stakeholders of NZEBs have not been found within the literature.

2.3 Stakeholder Analysis and Methods

Stakeholder analysis has been applied broadly in construction engineering and management (Olander and Landin 2005; Jepsen and Eskerod 2009; Yang et al. 2011; Wang et al. 2012). In this type of analysis, stakeholders are identified and analyzed in terms of their power, interest, and influence. Based on stakeholder analysis, strategies are developed in order to improve stakeholder management and implement project goals. Stakeholder mapping techniques have also been proposed by researchers to map the power/interest of stakeholders (Mendelow 1981; Johnson and Scholes 1999). Furthermore, Olander and Landin (2005) have proposed a power/interest matrix with a scale from 0 to 10 applied to a case study, which clearly maps each stakeholder for each project phase.

Stakeholder identification is often conducted through focus group or interview methods (Wang et al. 2012), both of which are growing trends in research. The focus group interview is a research method in which participants discuss a particular topic under the direction of a moderator who guides the interaction and the discussion in order to maintain focus on the topic at hand (Stewart et al. 2007).

McDonagh and Langford (2003) have introduced a systematic focus group method for product development. The mechanism of focus group methodology is that the interactive and synergistic nature of group discussions allows researchers to solicit deeper insight into how and why people think and behave as they do. Focus groups may be used for cases either when information is unknown or when a problem has been encountered. Stewart et al. (2007) have discussed focus group methodology in detail, including participants, moderator, interview guide, and process, and have summarized the following observations: (1) a typical focus group interview usually lasts 1.5 to 2.5 hours; (2) the moderator is the key to ensuring that the focus group discussion goes smoothly and remains focused; depending on the objectives of the research, the moderator may be more or less direct with respect to the discussion; and (3) the focus group is carried out with the collection of both qualitative and quantitative data. Li and Wang (2013) have employed the focus group method to investigate the perceived value of solar energy housing among farmers in Chongqing, China. Four factors—price, quality, social values, and emotional values—were taken into account; the authors discovered that the price was the most important factor among participants, and quality the second-most. Barry et al. (2008) have applied the focus group method in order to determine the most important factors for sustainable energy technology selection, and compared and merged their results with those in the existing literature.

Survey is another popular information collection method for social study, which involves that participants answer structured and predefined questions, the answers to which constitute the data to be analyzed (Pinsonneault and Kraemer 1993). Generally, a survey involves the collection of data from a segment of the population, known as the sample. Findings from the sample can then be extrapolated in order to draw conclusions about the entire population. Pinsonneault and Kraemer (1993) discuss the different purposes of survey research: exploration, description, or explanation. Exploratory surveys are used to gather more information about a certain topic and determine the range of responses from the population. With a descriptive survey, the distribution of an opinion/situation/event within a population is studied. Survey aiming explanation tests theories and relationships among variables. The key aspects of survey research include research design, sampling procedures, and data collection methods. Elias (2015) has described the purpose of a well-designed questionnaire as to communicate success and/or facilitate continuous improvement.

Social network analysis is a typical method used to identify and analyze the underlying structure of stakeholder relationships (Yang et al. 2011). First proposed by Rowley (1997), this technique is considered useful by scholars of stakeholder management in construction. In this technique, a network is defined as a system of relationships between nodes, which are distinguished by different characteristics. Social network analysis provides an analytic tool for studying interactions among stakeholders and exploring information concealed within complex social systems (Uzzi 1997; Troshani and Doolin 2007). Research on social networks has been conducted within the construction domain with respect to bidding competitions, crisis conditions, and information exchange (Loosemore

1998; Pryke 2004), as well as organization and project management (Chinowsky et al. 2008). Social network analysis effectively uncovers the attributes of the relationship network, as well as the mutual influence on stakeholders. Borgatti et al. (2013) have systematically introduced the theory on social networking analysis, including mathematical background, data collection, visualization, and such metrics as density, centralization, degree centrality, betweenness centrality, and closeness centrality.

2.4 Energy Performance Simulation and Programs

Energy simulation at the design stage provides a powerful quantifying tool to estimate energy performance for different scenarios. Bucking et al. (2013) have proposed a hybrid evolutionary algorithm in order to minimize the energy consumption of an NZEH, with EnergyPlus as the energy simulation tool. The algorithm proposed in their study uses information gain to improve algorithm convergence by means of targeted deterministic searches, and the results provide an optimal design scenario for the NZEH case. In another study, to target affordable NZEHs within an $80,000 incremental cost, ESP-r has been used as the simulation tool for 80,000 simulation runs, and Particle Swarm Algorithm is applied to search cost-optimal technology combinations (Carver and Ferguson 2012). Kirney et al. (2012) have proposed a manual cost optimization method based on energy simulation using HOT2000 windows version. For each of three building cases in the Kirney et al. study, the transition point signifying a cost jump for building envelope was identified by calculating the additional cost of saved energy per unit for each upgrade. Parekh et al. (2014) have investigated the progressive improvement of the energy efficiency of homes in Canada using HOT2000 as a tool, and estimated additional costs associated with reducing energy consumption by increments of 25%, 50%, 75%, and net-zero energy in different Canadian regions. A transient system simulation tool, named as TRNSYS, is also utilized to simulate the energy performance of buildings and solar energy systems (Beckman et al. 1994, Magnier and Haghighat 2010).

Other recent studies have considered the impact of occupant behaviour on building energy consumption. Fabi et al. (2013) have analyzed the impacts of window openings on the energy consumption and indoor environmental quality using IDA (ICE) as a simulation tool. Peng et al. (2012) have proposed a method to simulate occupant behaviour, and the proposed method was applied into DeST-m simulation program. The energy sensitivity introduced by occupant behaviour and weather conditions is another research area; Kneifel et al. (2015) applied EnergyPlus in order to analyze the energy performance sensitivity of an NZEH with regard to seven factors of building design, air leakage, occupant behaviour, weather, building orientation, and heating and cooling set-point temperatures. Crawley et al. (2008) compared the capacities of building simulation programs. Currently, representative and widely used building energy simulation programs include: (1) HOT2000, which was developed by Natural Resources Canada and is the official building simulation software of the Government of Canada; (2) EnergyPlus, which was developed by the US Department of Energy; and (3) ESP-r, which was initially developed in the United Kingdom, and is an integrated modelling tool for thermal, visual, and acoustic performance of buildings and energy use. HOT2000 has been used for residential building energy analysis and rating in Canada since 1987. The predecessor of HOT2000 is HOTCAN, which was written in the Apple Basic language. The development of HOT2000 was carried out in two primary versions, an Interactive (Windows) Version written in the Mega-Basic language, and the Batch Version written in FORTRAN. In 1988, Batch Version 5.04f was released, and previous interactive programs could be translated into ASCII batch-compatible format. Currently, the Batch Version 10.52 of HOT2000 is compatible with the Interactive Version 10.51 (Natural Resources Canada 2010).

As for renewable energy, such programs as RetScreen and PVWatt are typically used to estimate the energy generation. RETScreen, which has been developed by the government of Canada, is a simulation tool for energy efficiency, renewable energy, and energy performance analysis (Natural Resources Canada 2014). PVWatts has been developed as an online tool by the Natural Renewable Energy Laboratory of the Department of Energy, and is used to estimate the energy generation of solar PV systems; such parameters as system size, module type, array type, system losses, tilt angle, and azimuth angle are used to estimate the energy generation of PV systems (Natural Renewable Energy Laboratory 2015).

2.5 Energy Performance Monitoring and Analysis

While energy simulation provides an approach to quantify energy consumption of the occupancy phase for NZEHs, the simulation results are the average expectation and do not incorporate occupant behaviour. The results thus cannot reflect the actual performance of NZEHs, which must be monitored and assessed.

Rodriguez-Ubinas et al. (2014) have described an energy efficiency contest of zero-energy homes in Europe; the interior comfort, functioning, and energy performance of zero-energy homes were monitored for 12 days, and, based on the collected data, comprehensive energy efficiency was evaluated by a jury of international experts. Rodriguez-Ubinas et al. (2014) also have proposed such recommendations as installing separate power meters to monitor heating, ventilation and air conditioning (HVAC), and hot water heating in future research. Ridley et al. (2014) have utilized a designed monitoring system to measure the actual performance of two passive houses, which is another energy efficient house type with passive energy savings. Norton et al. (2013) demonstrated a comparison between the modelled and measured energy performance of NZEHs in Hawaii; in addition to the monitored performance feedback to homeowners, the research results will support the energy efficient designs in such tropical climates as Hawaii. Sharmin et al. (2014) have proposed a monitoring framework of a building under occupancy conditions using sensor technology; in their study, various types of sensors are utilized to monitor energy consumption, thermal performance of the building envelope, and indoor air quality (IAQ). The sensor data in their study is transmittable, storable, and downloadable, making it useful for various analyses and comparisons with design simulation. Currently, there exist two methods to monitor the actual energy performance of buildings: (1) meter readings or utility bills, and (2) sensor technology. Meter readings or utility bills can be used to collect rough data about energy usage and generation, as exemplified in a study by Thomas and Duffy (2013). However, the detailed energy consumption of a specific device must be investigated, and sensor technology is applicable for detailed energy monitoring of this nature.

Based on the collected data, data analysis and data mining are commonly applied for building operation data, and a number of studies on the application of data analysis and data mining on building energy consumption have been conducted. Yu et al. (2013) have reviewed commonly used data analysis methodologies of building operation data, and categorized them as follows: indicator method (e.g., energy use intensity), statistical method (e.g., correlation analysis), and building simulation. To overcome the weaknesses of each method and the barriers of building performance analysis, Yu et al. (2013) proposed a data mining methodology, incorporating classification, cluster, association, and decision/regression tree in order to model building energy consumption and identify influencing factors. Cios et al. (2007) have introduced a comprehensive account of the knowledge body on data mining, including supervised/non-supervised data mining, classification, regression, association, clustering, and such methods as decision tree, support vector machines, Bayes theorem, and classifier fusion, among others. Robnik-Sikonja and Kononenko (1997; 2003) studied the application of ReliefF algorithm for attribute estimation.

2.6 Building Envelope and Mechanical Devices

Building envelope and mechanical system are utilized as two fundamental approaches in terms of energy conservation and energy recovery for NZEH design; a properly designed building envelope and mechanical system may significantly reduce the energy demand of houses during the occupancy phase and recover the energy used as much as possible. The Canadian Wood Council (CWC), which is the national association representing manufacturers of Canadian wood products used in construction, provides designers and builders with online representative and prescriptive wall assembly solutions, complying with the 2012 amendments to the 2010 National Building Code (CWC 2014). Stud and insulation configuration are the central features of building envelope. In addition to the traditional stud configuration, complex wall structures, e.g., double-stud wall, offset wall, and truss wall, have also been developed, and all of these structural configurations are described in terms of physical characteristics, buildability, and cost (Building Science Corporation 2014). Insulation is the most pertinent part of building envelope in terms of energy performance, comprising two categories: cavity insulation and continuous insulation. The commonly used cavity insulation category includes both batt and spray foam insulations. Continuous insulation types include semi-rigid or rigid batt and board insulation, e.g., expanded polystyrene (EPS) and extruded polystyrene (XPS). The primary mechanical systems, which are utilized as the means of energy conservation and energy recovery, include HVAC, hot water heating, and drain water systems. Correspondingly, the contribution that mechanical systems can make for NZEH design include: (1) improving the overall energy efficiency of NZEHs by use of high efficiency mechanical systems for HVAC and hot water heating; and (2) recovering portion of the energy used by utilizing energy recovery technology for ventilation and drain water system. Numerous research studies have been conducted on mechanical system design with respect to ventilation, hot water heating, and heat pump technology (Homoda et al. 2013; Dieckmann et al. 2009; Zhang et al. 2014; Verhelst 2012; Hu et al. 2013).

2.7 Renewable Energy

The key component of NZEBs is the introduction of technologies that permit the use of renewable resources. There are several renewable resources that can be utilized to generate renewable energy such as sunlight, wind, and geothermal energy. In the case of the NZEHs studied in this research, which were built by Landmark, only solar energy is taken into account, considering pertinent legislation that allows for solar energy generation, as well as the constructability issues which inhibit the use of geothermal and other renewable resource energy for residential dwellings. Photovoltaic (PV) power generation has long been known as a clean energy technology with convenient installation. Musall et al. (2010) have summarized typical solution sets used in NZEBs, and they found that, in every case they studied, solar PV was utilized as a technology for electricity generation. Although in the past the use of solar PV systems has been cost-prohibitive, the market has recently seen a sharp decrease in the average cost of an installed solar PV system from $7.20/W in 2007 to $2.50/W in 2013 (Lofthaug 2013). Martinopoulos and Tsalikis (2014) have analyzed a typical solar energy system used in a Nearly Zero Energy Building in Greece in terms of technique, economy, and environment. Their results revealed that "the solar energy system covers at least 45% of the total heating loads while the payback period is as low as 4.5 years".

Along with the declining price of solar PV systems, another driving factor in the widespread commercial deployment of solar PV systems is such incentives as PV feed-in tariffs (FiTs). FiTs have been available in approximately 50 countries in recent decades (REN 21 2011). An incentive program in Alberta, Canada, for example, is Micro-Generation, which came into effect in January, 2009. Micro-Generation, which constitutes a set of rules, allows Albertans to generate environmentally-friendly electricity and receive credit for the electricity sent into the electricity grid (Alberta Energy 2009). As of 2013, the total cumulative capacity of solar PV systems has reached almost 4,000 kW in Alberta. Meanwhile, the efficiency of solar PV depends on the geographical region in which it operates, on the directional orientation of the house, on the installed angle of panels, and on the removal of snow from the panels. Generally, units which are south-facing and installed at an angle close to altitude and which are clear of snow will result in high efficiency (Howell 2013).

Based on the literature review, the following research needs are identified and addressed in this research: (1) stakeholder analysis needs to be conducted for NZEHs to investigate stakeholder relationships and the impacts of NZEHs on the stakeholders; (2) informed energy simulation needs to be conducted for NZEH design decisions; (3) detailed energy monitoring is required in order to investigate the actual energy performance and the potential information; and (4) initial cost analysis needs to be conducted to promote NZEHs, incorporating the results from the stakeholder analysis, the informed energy simulation, and the detailed energy monitoring.

Chapter 3 Stakeholder Analysis of NZEHs

The market acceptance conditions of NZEHs and the impacts on stakeholders are identified in this chapter, with the following detailed research objectives pursued: (1) identify influential stakeholders for each stage in the NZEH lifecycle, and rate the interest and influence of each stakeholder; (2) analyze the stakeholder relationships for NZEHs; and (3) discover the extent of market acceptance and the impacts on stakeholders of NZEHs.

3.1 NZEH Stakeholder Analysis Methodology

To achieve the proposed research objectives, the following research methodologies are applied corresponding to the research objectives: (1) a focus group study is applied to identify the stakeholders of NZEHs and to rate the interest and influence of each stakeholder; focus group study is also used to finalize the questionnaire for the survey; (2) survey is utilized to collect information with regard to market acceptance and impacts on stakeholders of NZEHs; and (3) social network analysis is employed to analyze the stakeholder relationships of NZEHs. Based on the collected information and the network metric analysis, holistic information with regard to the stakeholders of NZEHs is identified, as shown in Fig. 3-1.

(1) Stakeholder Identification

The stakeholders of NZEHs are determined based on the phases and activities which constitute the lifecycle of an NZEH; the lifecycle of an NZEH can be categorized into the pre-construction phase, construction phase, and occupancy phase, with each phase involving different stakeholders. Facilitated by the application of focus group study, with 12 attendees involved, the stakeholders of NZEHs are identified as follows (also see Fig. 3-2).

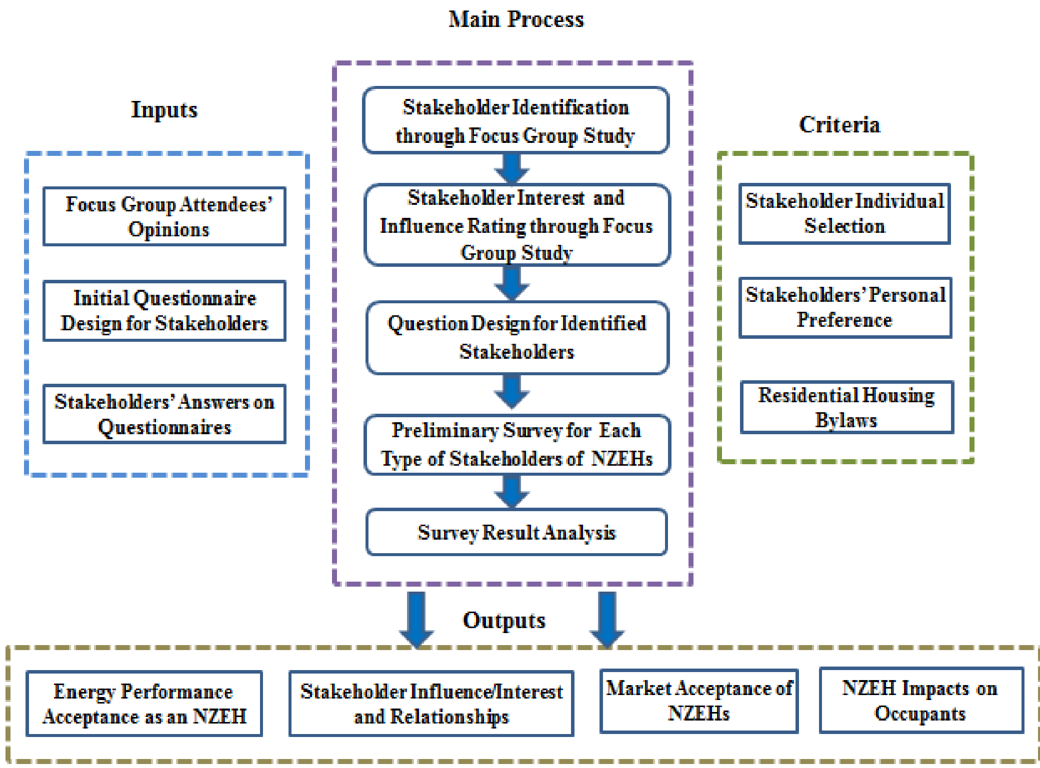


Fig. 3-1. Stakeholder Analysis Methodology

- The pre-construction phase is divided into two sub-phases—before and after the signing of the contract: during the period *before signing of contract*, homebuyer, sales personnel, developer, and financial institution are involved as stakeholders; *after signing of contract*, designer, estimator, project manager/coordinator, sales personnel, and trades and supplier are the related stakeholders. Additionally, regulatory personnel and coordinator are involved within the permitting process.
- Construction phase: stakeholders consist of homebuyer, superintendent, project manager/coordinator, trades/supplier, and inspector.

- Occupancy phase: the stakeholders at this stage are occupant, warranty provider, and financial institution.

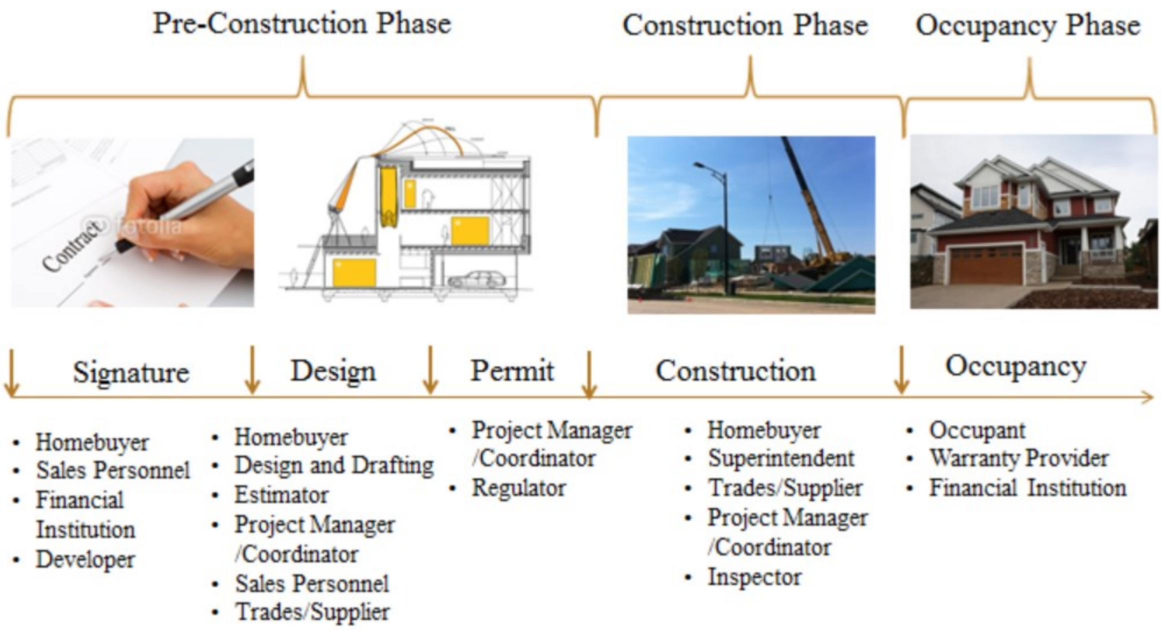


Fig. 3-2. Stakeholder Identification

(2) Stakeholder Rating

In this research, each identified stakeholder is rated with regard to interest and influence; interest is defined as how interested each stakeholder is to impress their expectations on each phase, and influence is used to measure how much power/influence each stakeholder has on each stage. With the application of focus group study, the respective degrees of interest and influence of the identified stakeholders are rated for each stage using a scale from 0 to 10.

(3) Questionnaire Design and Survey

A stakeholder list and the corresponding questionnaires are pre-designed prior to the focus group study, and the finalized list and questionnaires are compiled in accordance with the comments and responses from the focus group study. The questionnaires are designed for a total of thirteen identified stakeholders: developer, estimator, financial institution, homebuyer, inspector, NZEH occupant, design and drafting personnel, project manager/coordinator, regulator, sales, superintendent, trades/supplier, and warranty provider. Subsequently, a survey is employed to collect the opinions of each type of stakeholder. A survey link, created in Google Forms, is sent out via e-mail to contacts from industry and municipal directories, and there are 69 responses for this survey in total.

(4) Analysis of Results

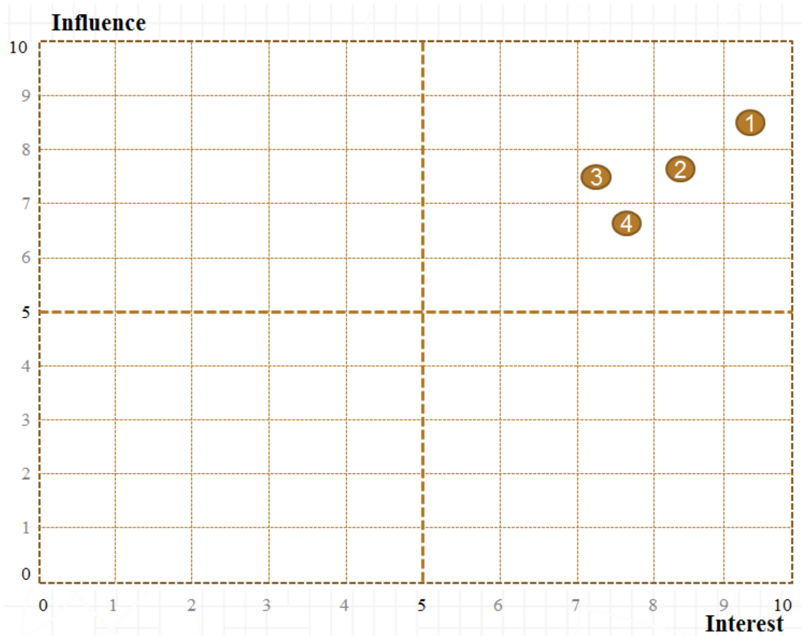
Based on the survey results, the following analysis is conducted: (1) the market acceptance conditions with respect to NZEH properties and prospective buyers are identified and characterized; (2) the energy performance acceptance is identified for NZEHs; (3) the impacts on the stakeholders arising from the potentially increased adoption of NZEHs are investigated and analyzed in detail; and (4) the social network is built and analyzed for the stakeholders of NZEHs.

3.2 Stakeholder Influence and Interest, and the Dynamics

As mentioned above, various stakeholders are involved in each stage of the NZEH lifecycle, and they exert different levels of interest and influence at each stage. The interest and influence rating results are displayed in Table 3-1 and in Fig. 3-3 to Fig. 3-7.

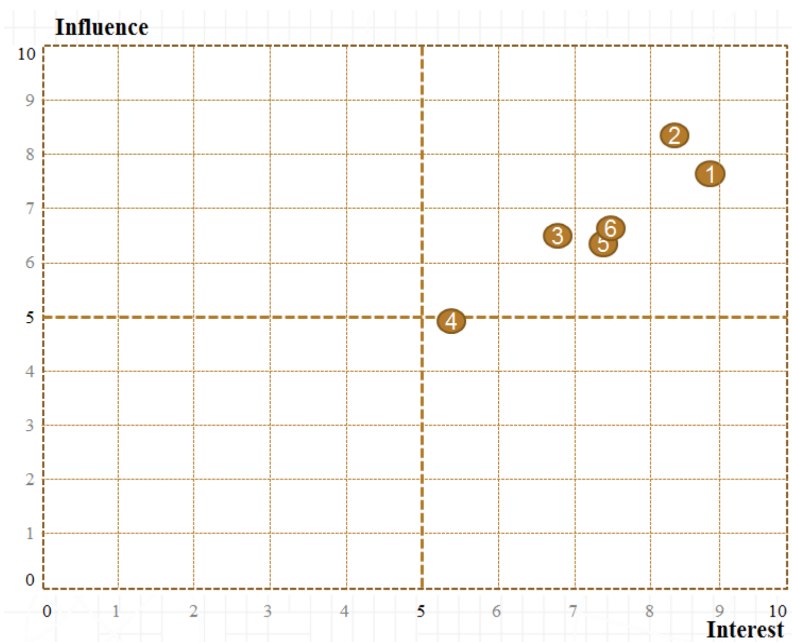
Table 3-1 Stakeholder Interest and Influence Rating

Phase		Developer	Design and Drafting Personnel	Estimator	Financial Institution	Home-buyer	Inspector	NZEH Occupant	Project Manager/ Coordinator	Regulator	Sales Personnel	Superinten-dent	Trades /Supplier	Warranty Provider
Signature	**Interest**	7.7			7.3	9.3					8.4			
	Influence	7.8			8.4	9.5					8.7			
Design	**Interest**		8.3	6.8		8.9			5.3		7.4		7.5	
	Influence		8.2	6.5		7.7			4.9		6.3		7.7	
Permit	**Interest**								7.0	7.6				
	Influence								5.7	9.2				
Construction	**Interest**					8.4	7.5		5.9			8.5	7.75	
	Influence					5.7	9.0		5.6			9.0	7.45	
Occupancy	**Interest**				6.4			9.5						7.6
	Influence				7.0			8.2						7.4



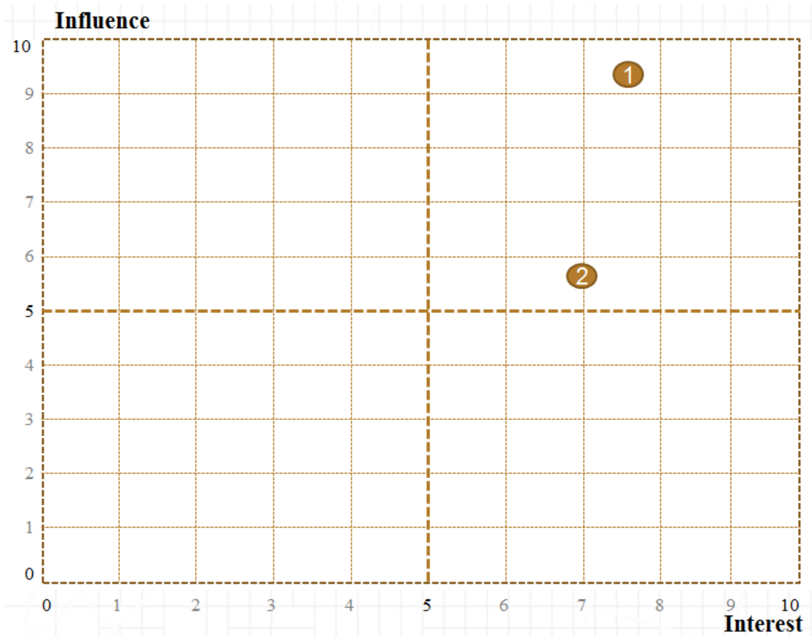
(1) Homebuyer
(2) Sales Personnel
(3) Financial Institution
(4) Developer

Fig. 3-3. Stakeholder Influence and Interest: Signature Phase



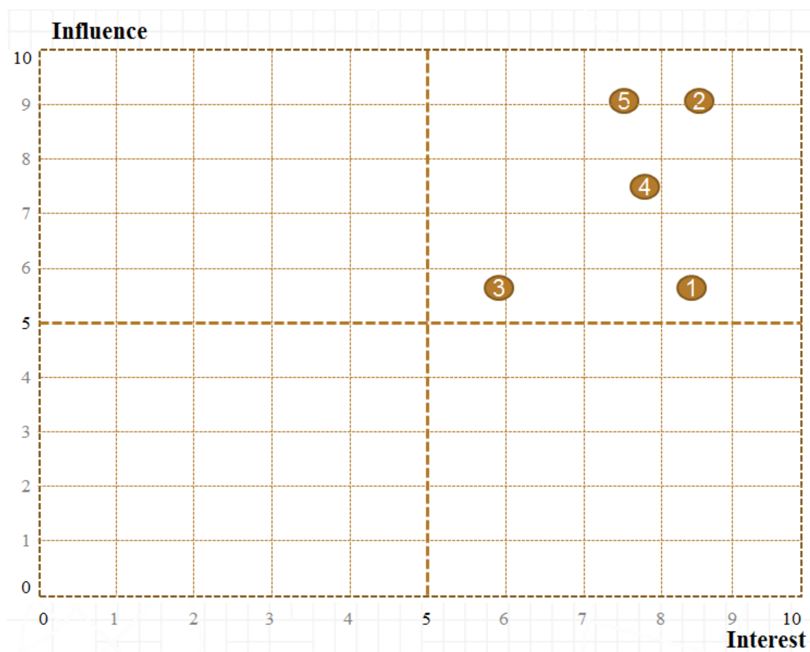
(1) Homebuyer
(2) Design and Drafting
(3) Estimator
(4) Project Manager/Coordinator
(5) Sales Personnel
(6) Trades/Supplier

Fig. 3-4. Stakeholder Influence and Interest: Design Phase



(1) Regulator
(2) Project Manager/Coordinator

Fig. 3-5. Stakeholder Influence and Interest: Permit Phase



(1) Homebuyer
(2) Superintendent
(3) Project Manager/ Coordinator
(4) Trades/Supplier
(5) Inspector

Fig. 3-6. Stakeholder Influence and Interest: Construction Phase

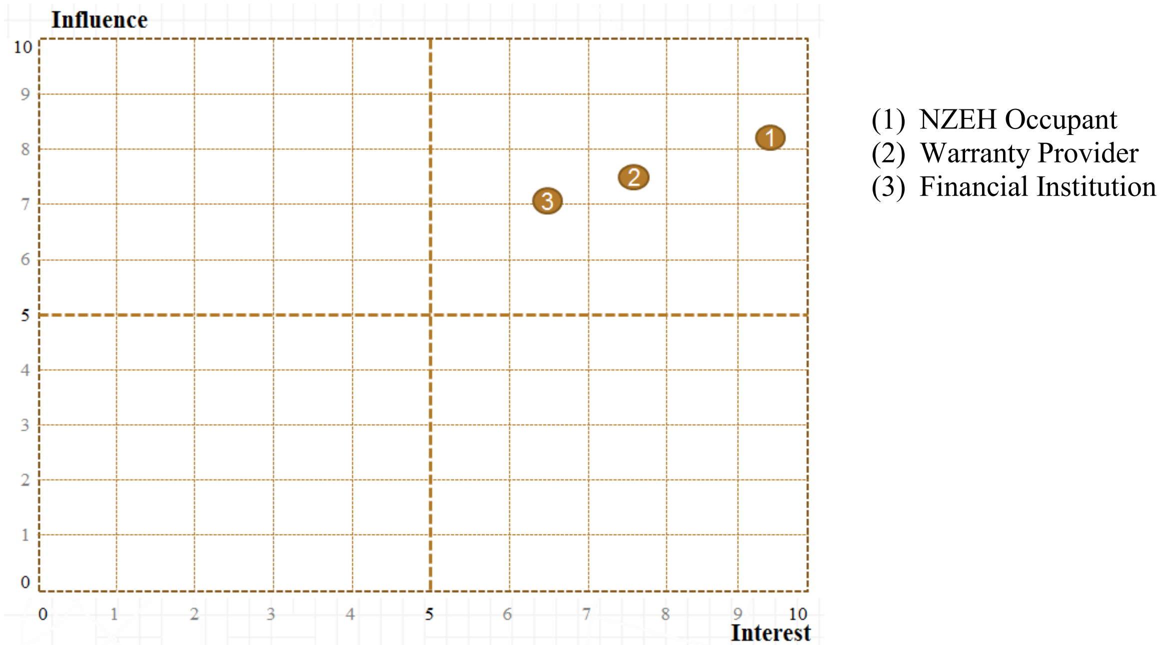
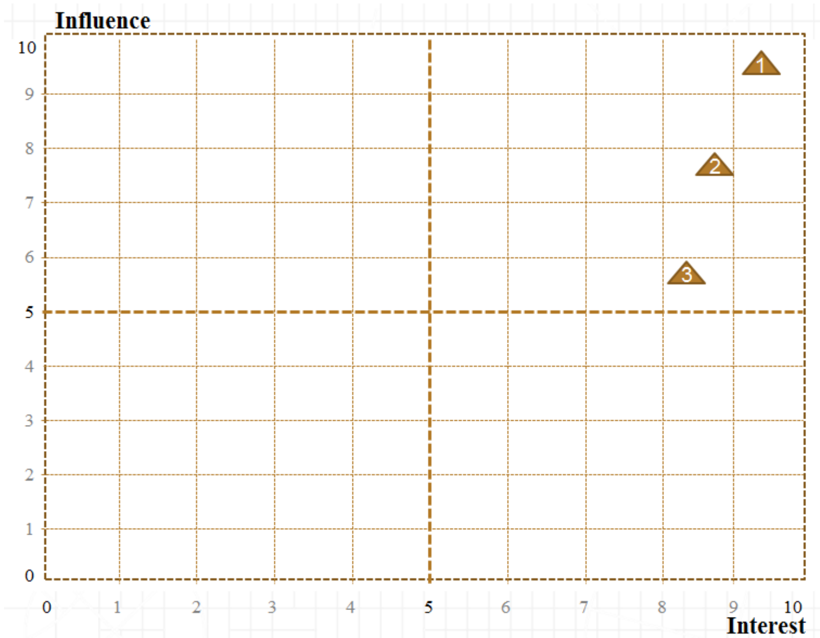


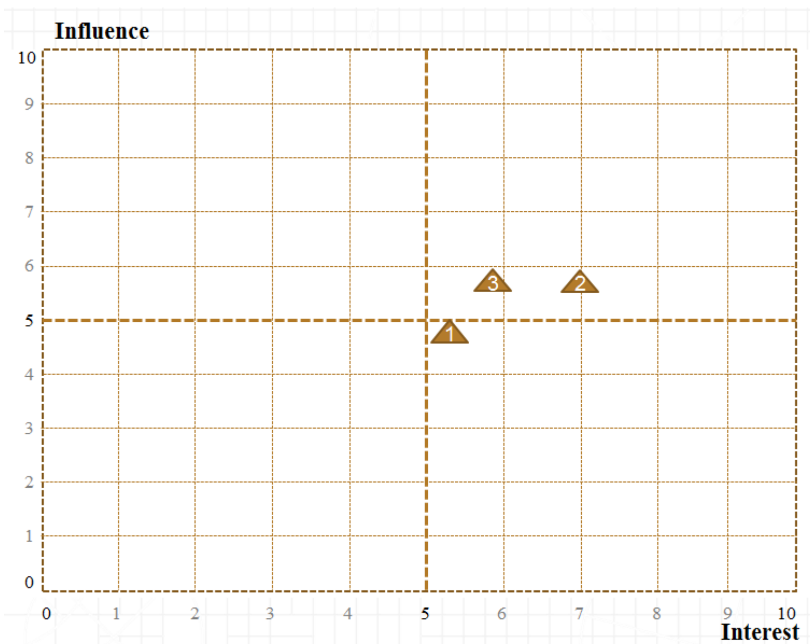
Fig. 3-7. Stakeholder Influence and Interest: Occupancy Phase

Two of the stakeholders remain present throughout various phases: (1) the homebuyer is involved in the signature, design, and construction phases, and (2) project manager/coordinator participates in the design, permit, and construction phases. In this research, the interest and influence changes that occur over different phases are referred to as interest and influence dynamics; the interest and influence dynamics are mapped for the homebuyer and project manager/coordinator, as demonstrated in Fig. 3-8 and Fig. 3-9.



(1) Signature Phase
(2) Design Phase
(3) Construction Phase

Fig. 3-8. Stakeholder Influence and Interest Dynamics: Homebuyer



1. Design Phase
2. Permit Phase
3. Construction Phase

Fig. 3-9. Stakeholder Influence and Interest Dynamics: Project Manager/Coordinator

Based on the results, the following observations are made regarding the stakeholder interest and influence and strategies that could promote NZEHs. (1) During the signature phase, the homebuyer is the stakeholder group that exerts the greatest influence and interest, and sales personnel and financial institution are in the second and third positions, respectively; thus the transfer of information and knowledge to the homebuyer can be a key determining factor in the sale of NZEHs. (2) For the NZEH design phase, the design team is rated as the stakeholder group with the greatest influence and interest, while the homebuyer also influences the home design; sharing energy saving designs with the homebuyer is thus important for customized NZEH design. (3) The regulator and inspector have high influence on NZEH design and inspection approval, so specialized information for NZEHs that is not relevant to the design of conventional homes must be interpreted appropriately for the benefit of the regulator and inspector. (4) For the construction phase, the site superintendent must also have specialized understanding of NZEHs. (5) As the controller of the occupancy phase, the occupant must have the necessary knowledge to operate the house efficiently, which will aid in the process of achieving net-zero energy balance. From the study of influence and interest dynamics, it can be observed that: (1) homebuyers have declining influence and interest over the development process of NZEHs, thus, earlier communication with the homebuyer will have a greater impact on NZEH development; (2) according to the project manager/coordinator influence and interest dynamics, project manager/coordinator contributes most during the permit phase, followed by the construction phase.

3.3 Analysis of Survey Results

3.3.1 Acceptance of Energy Performance

NZEHs are designed to achieve a net-zero energy balance; however, factors such as weather conditions and occupant behaviour introduce uncertainty with regard to energy performance and energy balance. In order to identify the acceptable level of energy balance necessary for a home to be considered an NZEH, the following survey question is designed: "In your opinion, a home qualifies as a net-zero energy home if the energy generation is ", with the answer options as "at least 100% of energy consumption", "at least 99% of energy consumption", "at least 95% of energy consumption", "at least 90% of energy consumption", and "Other (specify)". Among the 41 respondents to this survey question, comprising homebuyers, NZEH occupants, design and drafting personnel, and sales personnel, 19 indicated that energy generation must be at least 100% of consumption; nine respondents selected 90%, and eight indicated 95%. The average of the responses is 96.12%, and the answer distribution is provided in Table 3-2 and Fig. 3-10. The acceptance of energy performance as an NZEH reflects the stakeholder tolerance for an NZEH, and the average acceptance of energy performance as an NZEH can be referred to for NZEH design and variation analysis. From the response distribution, it can also be observed that design team and sales have higher expectation on the energy performance of NZEHs, while homebuyer and occupant indicate more tolerance.

Table 3-2 Acceptance of Energy Performance

Stakeholder	Energy Generation vs. Energy Consumption					Total	Average Acceptance
	75%	90%	95%	99%	100%		
Homebuyer		5	1	2	5	13	95.6%
NZEH Occupant	1		2	1	2	6	94.0%
Product Design & Development		2	2	1	7	12	97.4%
Sales		2	3		5	10	96.5%
Grand Total	1	9	8	4	19	**41**	
Overall Acceptance			96.12%				

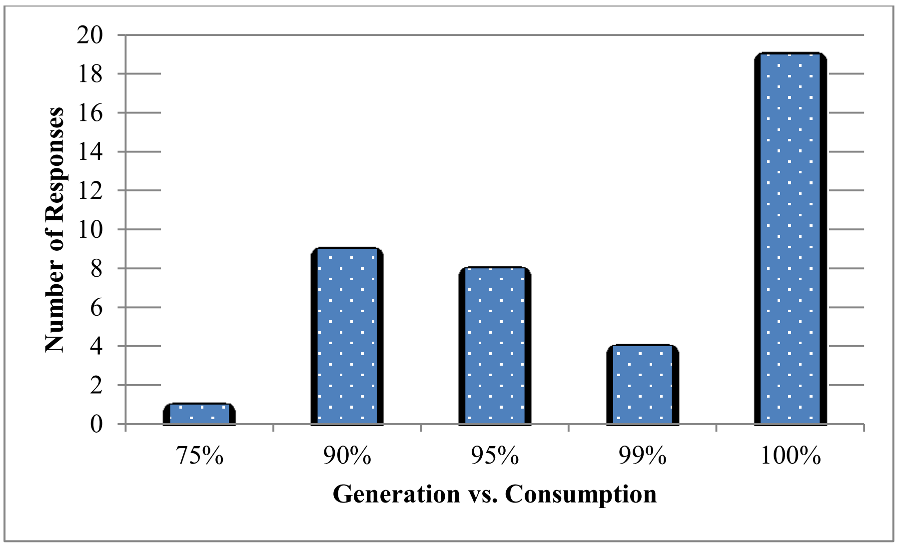


Fig. 3-10. Acceptance of Energy Performance as an NZEH

3.3.2 Market Acceptance

To identify the level of market acceptance of NZEHs, the following question is posed at the beginning of the questionnaire for homebuyers: "Are you interested in buying an NZEH?". The buyers who express interest in NZEHs are then asked the following questions: "What are the reasons contributing to your interest in buying an NZEH?", and "How much more would you be willing to pay for an NZEH compared with a conventional house?". Furthermore, the demographic characteristics of potential NZEH homebuyers, such as age group, education, field of work, and annual household income, are collected. The NZEH type preference, i.e., single-family, duplex, townhome, or apartment, is also investigated. For those homebuyers who expressing no interest in buying an NZEH, the questionnaire asks them to specify the reason(s) that deterred them from doing so.

A total of 13 homebuyers completed the survey, and out of the 13 respondents, 10 indicated an interest in buying an NZEH. Out of the three who indicated no interest in purchasing an NZEH, one cited the reason that NZEHs are too expensive, while the other two cited a lack of knowledge about NZEHs. The buyers interested in NZEHs are asked how much more they are willing to spend on an NZEH as compared with a conventional home. Half of the respondents (5 of the 10 interested buyers) reported a willingness to pay up to 5% more for an NZEH. Among the other half, two reported a willingness to pay up to 20% more, one each for up to 10% and 15% more, while another responded that their decision is dependent on the return. These results are provided in Fig. 3-11.

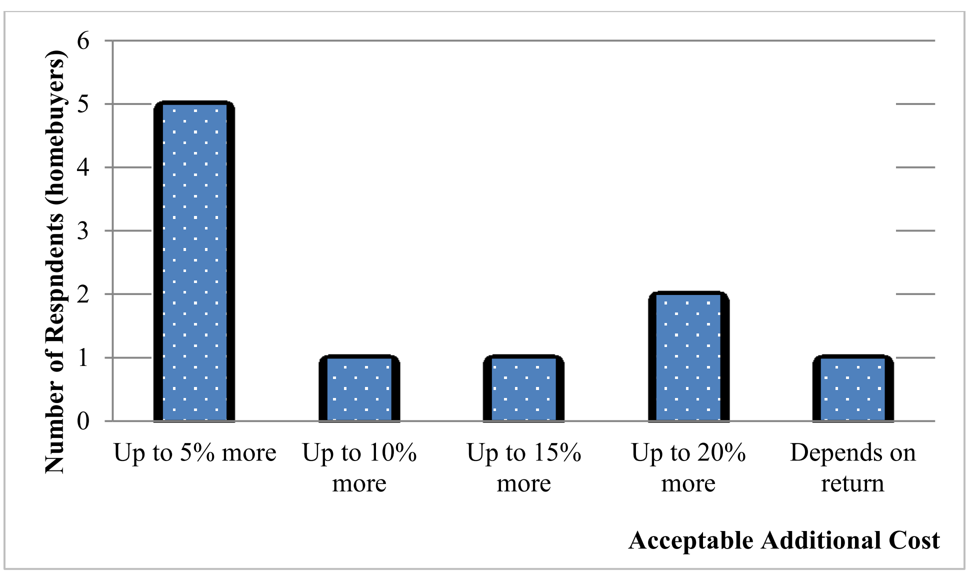


Fig. 3-11. Acceptable Additional Cost for an NZEH

In order to determine the demographics of homebuyers interested in buying NZEHs, the following information is gathered during the survey: age group, education, field of work, and annual household income. Out of the 10 respondents, two are between the ages of 21 and 30, five between 31 and 40, and three between 41 and 50, as shown in Fig. 3-12. Half of the potential buyers have trade/technical/vocational training, two have high school or equivalent education, two have a Bachelor’s degree, and one has a Master’s degree, as demonstrated in Fig. 3-13. In terms of field of work, two fall into each of the following categories: construction; mining, quarrying, and oil and gas extraction; and public administration. The remaining respondents work in the following fields as displayed in Fig. 3-14: professional, scientific and technical services; real estate, rental and leasing; renewable energy, and sustainable design/landscape. The majority of these respondents have an annual household income less than $149,999, with three in the range of $50,000 to $74,999, and three in the range of $75,000 to $149,000. One earns in the range of $150,000 to $199,000, two in the range of $200,000 to $299,000, and one in the range of $300,000 to $399,000. The income summary of a potential NZEH buyer is shown in Fig. 3-15. It is also determined that nine out of 10 NZEH buyers would prefer to purchase a single-family home while the other would prefer a duplex unit.

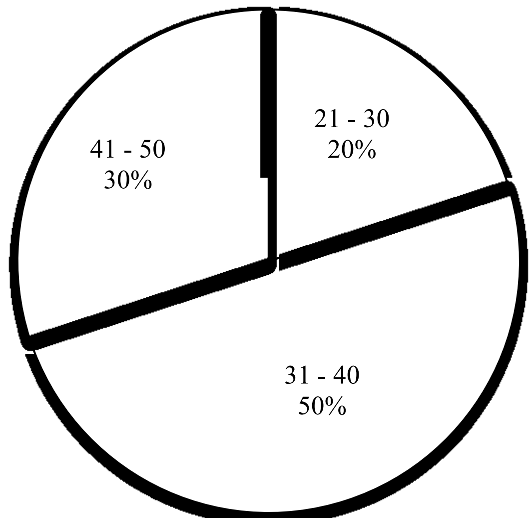


Fig. 3-12. Age Groups of Potential NZEH Buyers

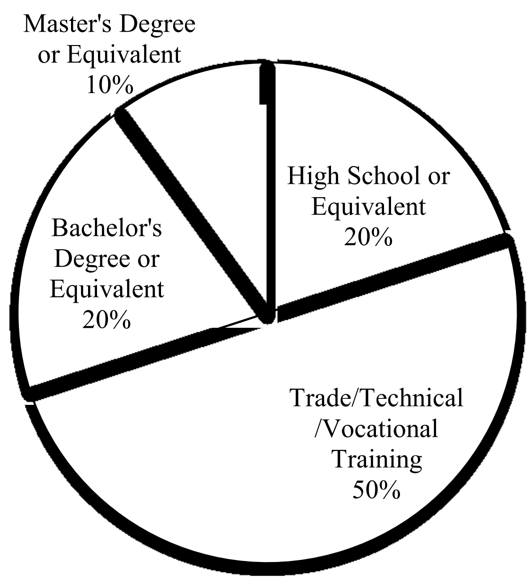


Fig. 3-13. Education Levels of Potential NZEH Buyers

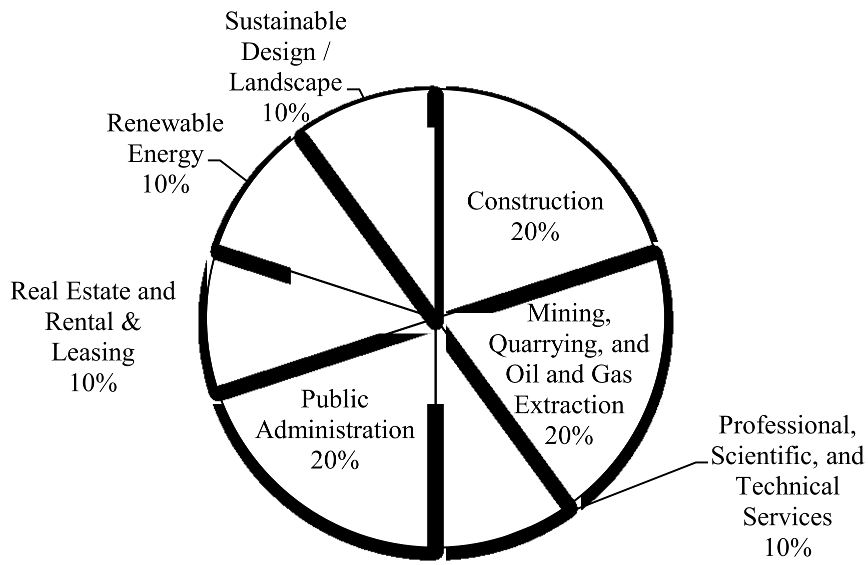


Fig. 3-14. Work Fields of Potential NZEH Buyers

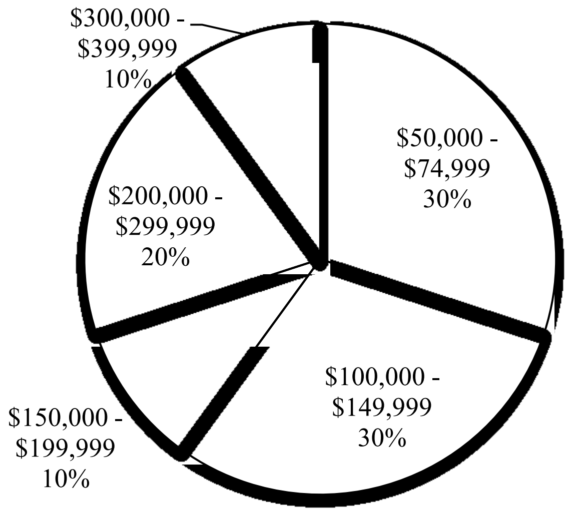


Fig. 3-15. Annual Household Incomes of Potential NZEH Buyers

3.3.3 Impacts on Occupants

Questions directed toward NZEH occupants are focused on the lifestyle impacts of living in a NZEH, such as, “Have your energy-saving habits changed since living in an NZEH?”, “Has your energy-saving awareness been improved since living in an NZEH?”, and “What do you consider to be positive aspects of living in an NZEH?”. NZEH occupants are also asked about the impacts of living in a

NZEH on the next generation and how they are impacted. The demographic characteristics of current NZEH occupants, such as age group, education, field of work, and annual household income, are also identified through the survey.

It is found that, among the six NZEH occupants who responded to the survey, all agree that by having lived in an NZEH, their energy habits have changed and their overall energy awareness has improved. Fig. 3-16 highlights the many positive aspects of living in an NZEH as reported by the occupants, the most common being the reduced utility bills for energy, followed closely by the positive impacts on future generations regarding energy saving and environmental protection. The least common positive aspect, identified by only two of the occupants, is that NZEHs are more comfortable than conventional homes, which conveys the information that the comfortability of NZEHs may be not identified at the perceivable level.

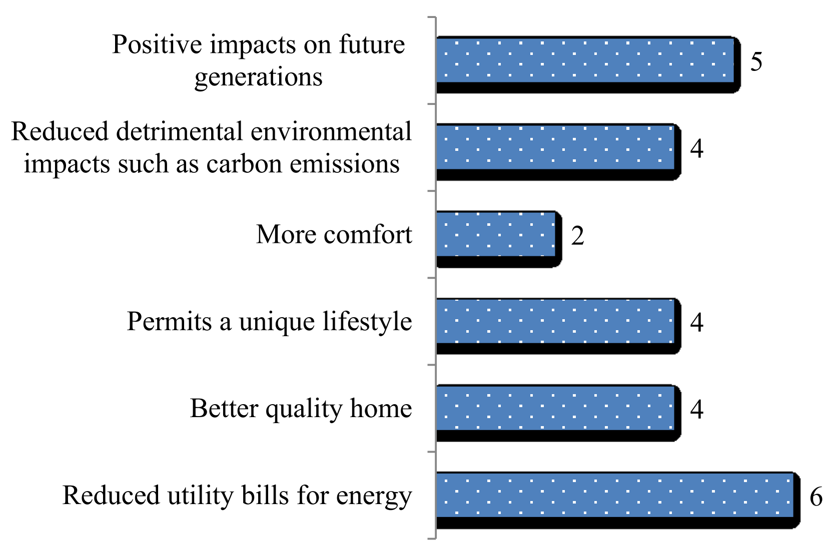


Fig. 3-16. Positive Aspects of Living in an NZEH

In Fig. 3-17, the energy saving habits adopted by the occupants are presented in terms of frequency. For example, it is found that five of the six occupants more frequently adjust their windows (i.e., open/close) and lights (i.e., turn on/off) to save energy due to living in an NZEH. Two of the occupants now regulate their thermostat more closely.

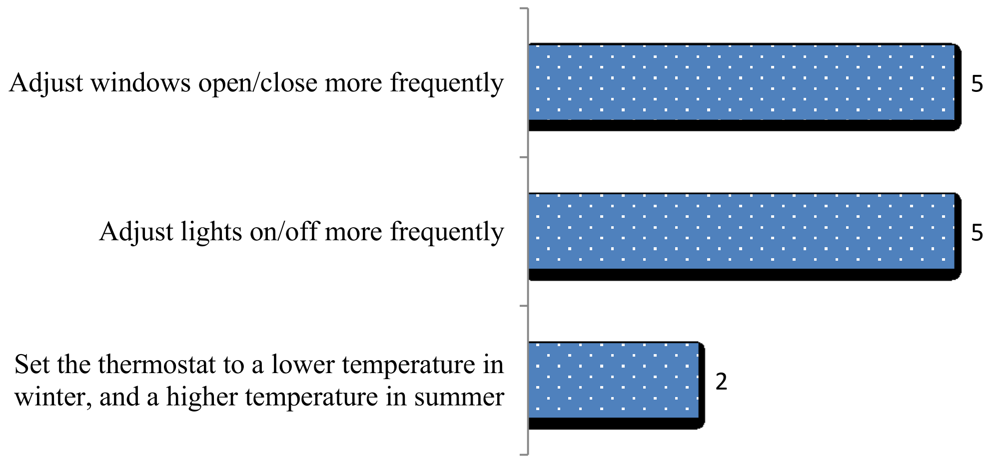


Fig. 3-17. Increased Energy Saving Habits

Three of the NZEH occupants reported taking other steps toward a sustainable lifestyle, including xeriscaping, owning hybrid vehicles, being involved in their community garden, and cycling to work. Most of the occupant respondents (5 out of 6) believe that living in an NZEH has impacts on future generations in terms of energy saving and environmental protection for the following reasons: (1) represents an opportunity to showcase energy awareness (as well as technology and affordability) to friends and family of the occupant; (2) conveys the message of being environmentally-friendly to the occupants' children; (3) demonstrates to homebuilders that there is demand for energy-efficient housing; and (4) allows for future occupants of the home to be exposed to NZEH living. NZEH occupants are also asked about the importance of energy consumption/generation monitoring; among the six NZEH occupants, four respondents indicated “must have”; one respondent indicated a strong desire for a monitoring system, and one cited “nice to have”. From the survey results, it can be observed that NZEHs introduce positive impacts on the occupants in terms of energy saving sense, energy saving habits, and impacts on the next generation without changing the lifestyle of the occupants.

3.3.4 Stakeholder Relationships and Social Network Analysis

Questions are designed in order to identify the amount of effort expended by NZEH stakeholders in terms of priority, energy, and time spent for the purpose of comparison with that expended for conventional homes. The responses elicited are on a 5-point scale: (1) “1” represents significantly less effort expended for NZEHs than for conventional homes; (2) “2” means slightly less effort expended for NZEHs than for conventional homes; (3) “3” denotes the same amount of effort expended for NZEH as for conventional homes; (4) “4” indicates slightly more effort expended for NZEHs than for conventional homes; and (5) “5” means significantly more effort expended for NZEHs than for conventional homes. All the respondents are found to have selected a number greater than or equal to 3, which means the stakeholders dedicate equal or more effort to NZEHs as compared with conventional homes. The stakeholder effort comparison between NZEHs and conventional homes indicates that the stakeholders of NZEHs are more dedicated than conventional homes, and NZEHs introduce positive impacts on the stakeholders. The summary of average effort among stakeholders for

NZEHs is demonstrated in Table 3-3, based upon which the stakeholder relationship is analyzed utilizing social network analysis, with UCINET software as the tool. The social network of NZEH stakeholders is illustrated in Fig. 3-18. Primary measurement indices for the network and individual stakeholders are analyzed as follows, based on the social network analysis theory proposed by Borgatt et al. (2013); corresponding suggestions are proposed for NZEHs following the social network analysis.

(1) ***Density*** is a cohesion measurement of a network, expressed as the number of ties as a proportion of the maximum number possible. A higher density means that more ties exist among stakeholders, which improves the conveyance of information and brings more impacts on stakeholders. Eq. (3-1) is used to calculate the density for direct networks, as follows.

$$D = \frac{l}{n(n-1)} \tag{3-1}$$

where D is network density; n is number of nodes, with maximal n(n − 1) edges in a network of n nodes; and l is number of actual edges.

The total number of ties in the NZEH network is 29, and the possible ties number 156, which results in a density of NZEH social network of 0.185. The network density indicates that the NZEH social network is a parse network, bringing only limited information and impacts on stakeholders.

Table 3-3 Stakeholder Effort of NZEHs

Stakeholders	Collaborating with												
	Developer	Estimator	Financial Institution	Home buyer	Inspector	Occupant	Product Development and Design	Project Manager/ Coordinator	Regulator	Sales Personnel	Superintend-ent	Trades/ Supplier	Warranty Provider
Developer								5.0					
Estimator							3.5	4.3		4.3		4.3	
Financial Institution				4.0		4.0							
Homebuyer													
Inspector								3.3					
NZEH Occupant													
Product Development and Design Personnel		4.0						4.3		4.5			
Project Manager/Coordinator		4.2		4.5			3.7		3.7		4.3		
Regulator								3.0					
Sales Personnel		3.9		4.2			3.8						
Superintendent								5.0				5.0	4.5
Trades/Supplier		3.6		3.4							3.4		3.0
Warranty Provider						5.0							

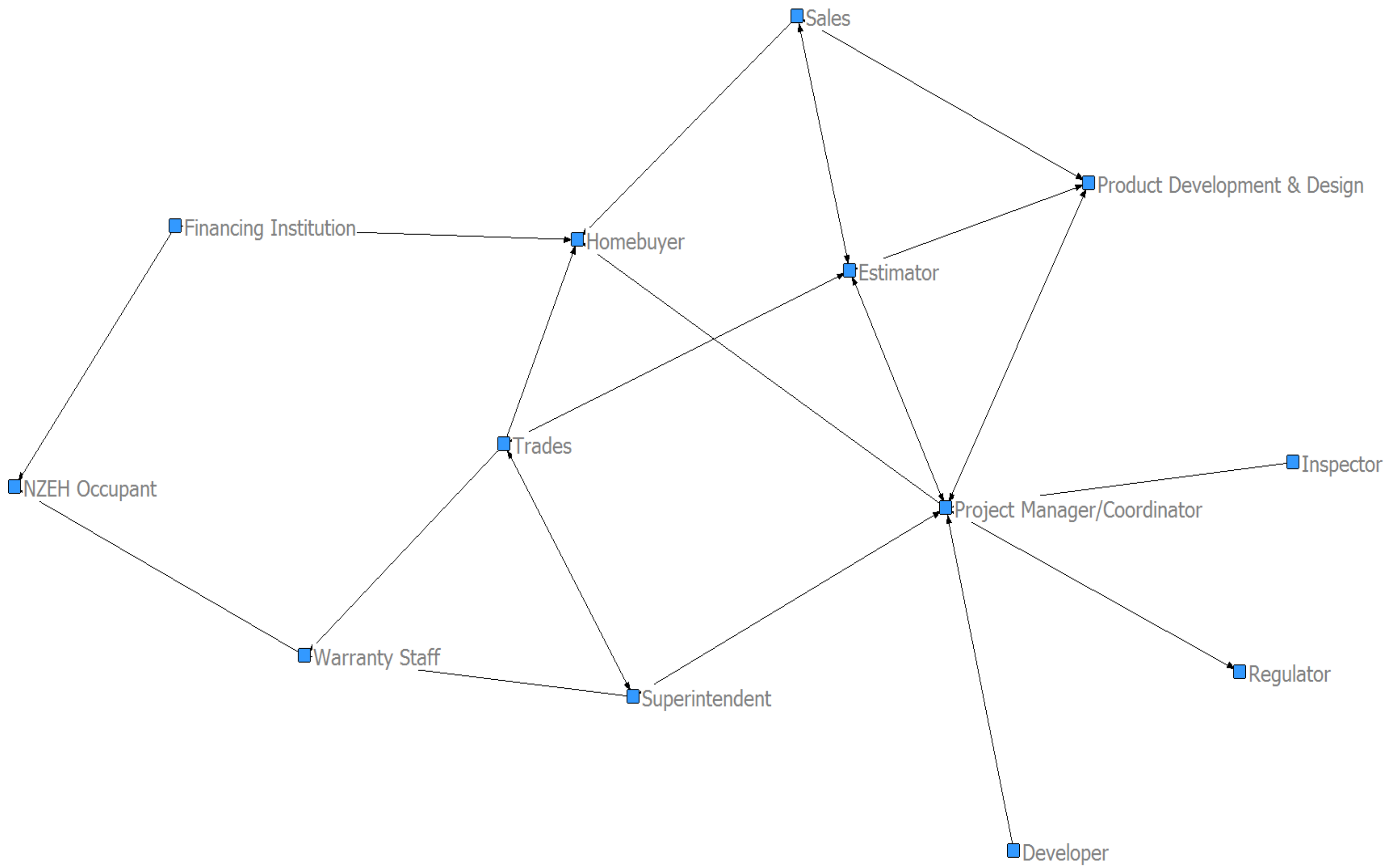


Fig. 3-18. Social Network of NZEH Stakeholders

(2) ***Degree centrality*** is used to measure the ties of a given node with others, which define a node's position in a network. For a directed network, the degree centrality is categorized as either out-degree centrality or in-degree centrality. A higher out-degree centrality means an individual has more connections with others, and has more potential influence on other stakeholders, while higher in-degree centrality indicates the stakeholder is more likely to be influenced *by* other stakeholders. Eq. (3-2) can be utilized to calculate the degree centrality, as follows.

$$C_D(n_i) = \frac{\sum_1^j e_{i,j}}{n-1} \tag{3-2}$$

where $C_D(n_i)$ is *degree centrality* of node n_i; j is number of nodes, which are connected with node n_i; $e_{i,j}$ is the edge between i and j; and $n-1$ is the maximal edges of n nodes.

(3) ***Betweenness centrality*** measures how often a stakeholder appears on the shortest path between two other stakeholders. It can be calculated as the summed proportions of geodesic paths passing through a given node, as in Eq. (3-3). A node with higher betweenness centrality is the potential controller of the flow through the network, and has the power to boost the information conveyed.

$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \tag{3-3}$$

where $C_B(n_i)$ is *betweenness centrality* of node n_i; $g_{jk}(n_i)$ is number of geodesic paths (i.e., shortest paths) that pass through a node n_i; and g_{jk} is the total number of geodesic paths between nodes j and k.

(4) ***K-step Reach*** (***Closeness) centrality*** is used to calculate the number of distinct nodes within *k* links of a given node, or how many nodes a given node can reach in *k* or fewer steps. It is the sum of ties of a node to other nodes in a network within *k*-step, measuring the extent to which a node is reached by other nodes or reaches other nodes. More specifically, the closeness is assessed in more detail with directions of nodes for directed network, in terms of *In-Closeness* and *Out-Closeness*. Out-Closeness measures the impact of the internal part of the node on the external environment, while In-Closeness measures the impact of the external environment on the internal part of the node. A higher In-Closeness centrality identifies that a node is more reachable by other nodes, while a higher Out-Closeness centrality expresses that a node is more capable of reaching other nodes.

$$C_C(n_i) = \frac{\sum_1^j e_{i,j}^k}{n-1} \quad (3\text{-}4)$$

where $C_C(n_i)$ is *closeness centrality* of node; $e_{i,j}^k$ is edge between *i* and *j* within *k* steps; and *n* is number of nodes in a network.

The degree, closeness, and betweenness centrality are calculated for all the stakeholders of the NZEH network, and the results are expressed in Table 3-4. From Table 3-4, it can be observed that: (1) project manager/coordinator is the most influential stakeholder for both distributing and receiving information, with the highest out-degree and in-degree centrality among all the stakeholders. For the parse NZEH network, project manager or coordinator is an appropriate medium by which to spread NZEH knowledge and information to other stakeholders efficiently. (2) Project manager/coordinator also has the highest betweenness centrality, which indicates that the project manager/coordinator is an information controller. The provision of professional training to the project manager/coordinator with regard to NZEH knowledge and information will best facilitate the spread of NZEH knowledge and information. (3) Homebuyer and NZEH occupant have zero out-closeness, while the homebuyer has an in-closeness of 0.83, and the NZEH occupant has an in-closeness of 0.33. The homebuyer is thus widely susceptible to information, while the NZEH occupant is comparatively isolated from information spread. Since occupant behaviour has a considerable impact on the energy performance of NZEHs, professional knowledge with regard to appropriate operation of NZEHs must be passed on to NZEH occupants. Additionally, energy monitoring and the result report may be considered as an approach to strengthen the knowledge and information for NZEH occupants.

Table 3-4 Centrality of Stakeholders

Stakeholder	Out-Degree Centrality	In-Degree Centrality	Betweenness Centrality	Out-Closeness Centrality	In-Closeness Centrality
Developer	0.08	0.00	0.00	0.50	0.00
Estimator	0.33	0.33	0.11	0.67	0.67
Financing Institution	0.17	0.00	0.00	0.17	0.00
Homebuyer	0.00	0.33	0.00	0.00	0.83
Inspector	0.08	0.00	0.00	0.50	0.00
NZEH Occupant	0.00	0.17	0.00	0.00	0.33
Product Development and Design	0.25	0.25	0.03	0.58	0.67
Project Manager/Coordinator	0.42	0.50	0.29	0.67	0.67
Regulator	0.08	0.08	0.00	0.42	0.50
Sales Personnel	0.25	0.17	0.01	0.42	0.33
Superintendent	0.25	0.17	0.09	0.67	0.58
Trades	0.33	0.17	0.06	0.67	0.42
Warranty Provider	0.08	0.17	0.07	0.08	0.33

3.4 Summary

With the application of focus group study, 13 influential stakeholder groups are identified across the lifecycle of NZEHs: homebuyer, sales personnel, financial institution, developer, design and drafting personnel, estimator, project manager/coordinator, regulator, superintendent, inspector, trades/supplier, NZEH occupant, and warranty provider. Based on the identified stakeholders, the influence and interest are rated for each stakeholder by the focus group study attendees using a 1-10 scale. Referring to the influence and interest rating, stakeholder strategic suggestions are proposed in order to promote NZEHs for each stage of the NZEH lifecycle. Focus group study is also helpful in finalizing the questionnaire design for the subsequent stakeholder survey.

From the survey results of 69 respondents, it can be observed that the average energy performance acceptance in terms of energy generation versus consumption is 96.12%, and the design team and the sales express higher expectation than do homebuyers and occupants. Most of the homebuyer respondents (10 out of 13) indicate an interest in buying an NZEH, and half of the potential home buyers can accept the additional 5% in price as compared to conventional homes. The demographics of potential buyers of NZEHs are identified from the survey as well. It is also found that 9 out of 10 potential NZEH buyers would prefer to purchase a single-family home, rather than other home types. NZEH occupants respond that living in an NZEH has increased their energy saving habits and overall energy awareness. They have adapted energy saving practices such as turning lights on/off and adjusting windows open/closed. Half of the NZEH occupants participate in activities such as sustainable gardening and transportation choices. Most of the surveyed NZEH occupants (4 out of 6) indicate with the response 'must have' a preference for energy consumption/generation monitoring systems. Living in these NZEHs allows the occupants to model awareness to their family and friends and develops the infrastructure for future sustainable building practices.

In the survey, a set of questions is designed to identify the amount of effort in terms of priority, energy, and time among NZEH stakeholders and to compare with that of conventional homes. The respondents indicate equal or more effort expended on NZEHs compared with conventional homes, which reveals that the stakeholders of NZEHs are more dedicated than those for conventional homes, and that NZEHs introduce a positive impact on the stakeholder relationships. Stakeholder relationships are analyzed using social network analysis, and suggestions are proposed for NZEH promotion based on the analysis of social network matrices of density, degree centrality, betweenness centrality, and closeness centrality.

This chapter proposes a generic framework of stakeholder analysis for NZEHs, by which holistic knowledge pertaining to NZEH stakeholders, including stakeholder influence and interest, market acceptance, impacts on occupants, and stakeholder relationships, is identified. This research thus contributes to the body of knowledge on NZEH stakeholders.

Chapter 4 Energy Simulation of NZEH Design

Energy simulation provides an approach to quantitatively evaluate the energy performance of design options for NZEHs. The following research objectives are pursued in this chapter: (1) identify energy performance for the design options of each building envelope component and mechanical device factor *individually*; (2) evaluate the energy consumption for the *combinations* of building envelope and mechanical device options, and identify the potential knowledge for NZEH design; (3) simulate the energy consumption for different temperature set-points, and analyze the impacts on the energy usage for space heating; and (4) simulate the energy generation from solar PV systems. The simulation results will support informed decision making for NZEH design.

4.1 Energy Simulation Methodology

Considering the common use of HOT2000 in industry and particularly in Canada, where it is the software tool of choice for federal government agencies, HOT2000 is selected to simulate the energy consumption. RetScreen is used to simulate the energy generation in this research. As mentioned in Chapter 2, appropriate building envelope and mechanical system are utilized as the primary approach to achieve the energy conservation for NZEH design. Therefore, the following key components of building envelope and mechanical system, which are used to define a house model in HOT2000, are considered for design options: main wall, roof, exposed floor, basement wall, basement floor, ventilation device, space heating and cooling system, and domestic hot water (DHW) tank. The configurations of these components (referred to as factors below) are manipulated and input as the simulation variables. To begin with, a house model is built using the Windows Version of HOT2000, and then the model is converted into a V71 & V80 file pair. The energy consumption is simulated both for the individual factors and for the design option combinations of all factors using the Batch Version of HOT2000, with the substitution of configuration for iteration (i.e., design option). Based on the simulation results, the following analyses are conducted: (1) the energy consumption is curve-fitted with each factor for the individual simulation; (2) the overall energy consumption is plotted with regard to each factor for the combination simulation; (3) the energy consumption is modelled with the design options of the simulation variables using linear regression and neural network (NN); (4) factor importance is ranked for the simulation variables based on the combination simulation results; (5) the energy usage for space heating is curve-fitted with temperature set-point, and the impact of temperature set-point is analyzed; and (6) the energy generation from solar PV system is simulated using RetScreen. The mechanism and methodology of the applied programs, the building code and bylaws, and the practical design options for NZEHs are the criteria of the research methodology. The overall energy performance profile with regard to each factor, the factor importance ranking, the linear regression and NN models, and the fitted curve functions are the outputs of this section. The research methodology is represented in Fig. 4-1.

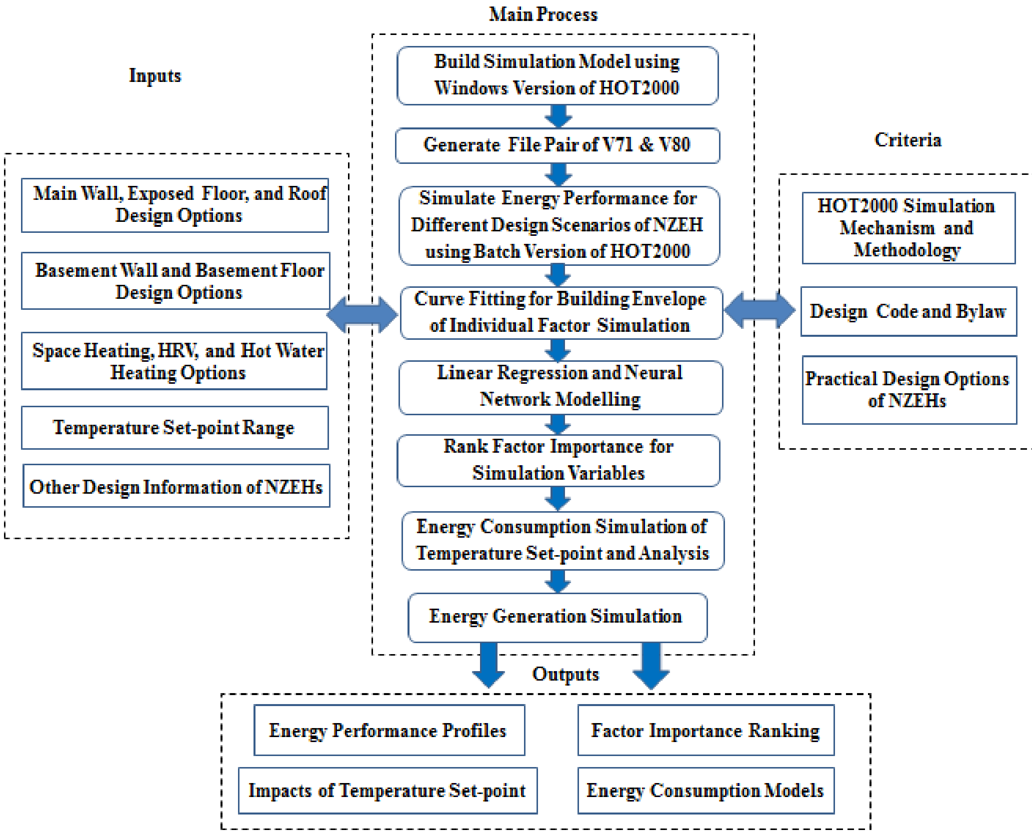


Fig. 4-1. Energy Simulation Methodology

The energy simulation flowchart using the Batch Version of HOT2000 is demonstrated in Fig. 4-2. The primary file types used for the Batch Version of HOT2000 include *job control file*, *job control record*, and *an executable core*. As job control files, a pair of V71 and V80 files, which are ASCII files, are utilized to define a house model. The V71 file is used to define the house parameters excluding house foundation, for which V80 is utilized to define the related parameters; the examples of V71 and V80 files are given in Fig. 4-3 and Fig. 4-4, respectively. Job control record defines such parameters as weather data and output fields; energy used for space heating and cooling, DHW heating, ventilation, and electricity base loads are the outputs and comprise the total energy consumption of NZEHs. Correct positioning of data in each row is critical, and any misalignment results in empty output. The detailed building envelope and mechanical system, which are applied for energy simulation, are presented in the following sections.

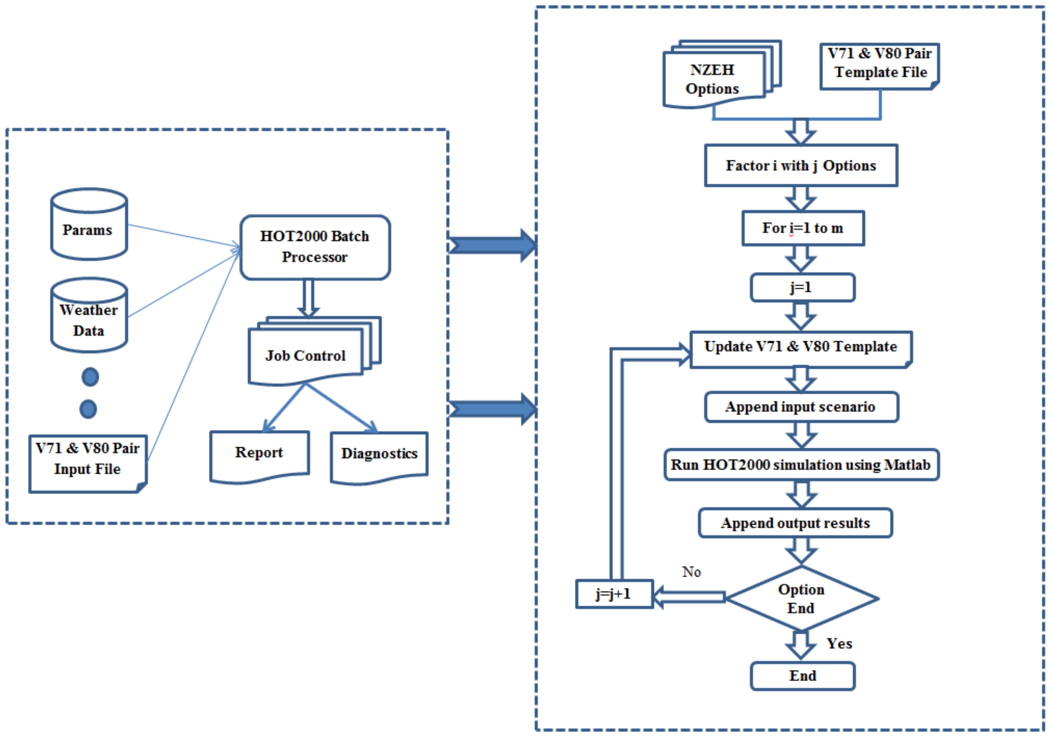


Fig. 4-2. Energy Simulation Flowchart

4.1.1 Practical Design Options of Building Envelope for NZEHs

Building envelope is employed as one of the energy conservation approaches for NZEH design, and a properly designed building envelope can help to reduce the energy consumption and to achieve net-zero energy balance for NZEHs. By integrating the CWC assembly solutions, the building codes, and the practical experience of the industry partner, the design options for primary building envelope with thermal resistance (RSI value) for NZEH design are displayed in Table 4-1.

```
                15  2  0     4MEDMONTON            5286N01436  612 3
,                             4112 Charles Link SW          z
Edmonton            Alberta            T6W 0Z4
9765 - 54 Avenue              Edmonton            Alberta            T6E 5J4
 1 3 0 1 1 1 2013 0 0 Rob W                           2014  3 10  5  3
11M    0000102122NUCF  2 21.0 19.0 15.0S   E   N   W    3 1 3 3 1 3
  1  3  0  0 0.400 1.000 0.550  22.0  24.0     0.0   247.2     0.0     0.0
  1 0Trion Triple one                     1    0.9570   0.8752   1.0566   38.1000   0.6200
  2 0Trito Triple two sunstop             1    1.4201   0.8752   1.0566   38.1000   0.3100
    3  1  2413J91000     5.182     2.787  0.50000     0.457    14.333
Ce  2  1  2413J91000    43.282   118.730  0.67000     0.457    14.034
    0000000000 101 1 4 1     2.768     6.858     4.051
    0000000000 101 1 6 6     2.768    33.680     5.580
    0000000000 101 1 810     2.463    48.768     5.500
Mw  1800IF0120     1 4 4     0.305    24.689     7.720
   M1   7     2.032     0.813     0.981
   M2   7     2.032     1.219     0.981
Do M2   7     2.032     0.813     0.981
    0000000000     2.134     1.087     7.380
    0000000000     4.267     2.044     8.480
    0000000000     6.096    28.150     7.270
Ef  0000000000     3.658     2.787     7.310
Mf  4512006300     8.970    80.454     0.759
   B1  233224  1     0.635     1.448     0.405     5.892     0.000     1.000
S  M3  0Trion  1     1.041     1.245     0.405     0.204     0.000     1.000
   M3  0Trion  1     1.245     1.245     0.405     1.067     0.000     1.000
   M3  0Trion  1     1.245     1.245     0.405     0.204     0.000     1.000
   M3  0Trion  2     1.549     0.940     0.405     1.067     0.000     1.000
E  D2  0Trion  1     2.032     0.305     1.524     0.152     0.000     1.000
   B1  233224  2     0.635     1.448     0.405     5.892     0.000     1.000
   M2  0Trito  1     1.524     0.914     2.134     0.253     0.000     1.000
N  D3  233204  1     1.524     0.610     0.405     0.610     0.000     1.000
   M3  0Trito  1     1.549     2.464     0.405     1.829     0.000     1.000
   M2  0Trito  1     1.524     2.438     0.405     0.701     0.000     1.000
   M3  0Trito  1     1.245     1.549     0.405     1.829     0.000     1.000
W  M2  0Trito  1     1.524     1.829     0.405     0.701     0.000     1.000
XNEYYYN2217   810.0    60.9    60.9  3.400  9.000  7.600  4.000 225.0 2  55.0 0 1
220   50.0   50.0    0.0   0.57  175.80.1500    5.0      11.0 100.0 1  131.6     0.0     0.0 2 1 1 2
3742100     10.0      6.1    0.200    0.650   0.150     0.0      0.0      0.0 2222222
N1     0.0     1.2     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
~~                            ~~                             2 1 0     1.10
AO Smith                      Voltex                           302.8 2 6 2 2     0.0     0.0 0.8400    0.00 0 0 0    0.
Venmar                        EKO 1.5
    0.0  -25.0  121.7  121.7   75.0   64.0    0.0    0.0   25.0
412   1.500 152.40  0.700  412   1.500 152.40  0.700
ZUBA Central                  ~~
0111     7.0    9.700     0.0   201.7     0.0   0.000     0.0    60.0     1.5 2
2122211222       0.0       0.0       0.0      555.0    2184.0
ES Appliances/CFL Lighting                                      DWHR: Thermo Drain
```

Fig. 4-3. V71 File of Batch HOT2000

```
2         200000     000000     0 0 0 0 0 0
   2   1   8   0   6   0   0   0   0   1  22   2
      9.08      8.08    124.00     40.75    866.00      0.00      0.00      0.00
      0.00      3.31     22.61      8.05      2.78     16.00     31.08      4.31
      0.00     21.25      0.00      0.00      0.00      0.00      0.00      1.00
      0.00   7863.28      0.00      0.00      0.00      0.00      1.00      0.00
00        101        00000     0000000    0000000000 4512006300 0000000000
```

Fig. 4-4. V80 File of Batch HOT2000

4.1.2 Practical Design Options of Mechanical Devices for NZEHs

Such high energy efficient mechanical devices as space heating furnace, hot water tank, and ventilator are another type of contributor to the energy conservation of NZEHs. Typical equipment types and configurations used by the industry partner are listed in Table 4-2, and are assessed with respect to energy performance in the following sections.

Table 4-1 Building Envelope Options

Main Wall		Attic		Basement Wall		Exposed Floor		Basement Slab	
Structure	**RSI** (K•m^2/W)	**Structure**	**RSI** (K•m^2/W)	**Structure**	**RSI** (K•m^2/W)	**Structure**	**RSI** (K•m^2/W)	**Structure**	**RSI** (K•m^2/W)
2×8 frame insulated with 12.7 cm SPF + 6.73 cm Spider	6.25	2×4 roof truss insulated with 8.89 cm SPF + 41.8 cm blown in	13.81	2×4 frame with drywall insulated with 8.89 cm Batt + 8.89 cm SPF	5.51	2×12 floor structure insulated with 17.78 cm SPF	7.31	10.16 cm EPS II under slab with thermal break at footing and wall	2.57
2×6 frame insulated with 13.97 cm SPF	4.22	2×4 roof truss insulated with 34.8 cm Blown-In	8.85	2×6 frame insulated with 5.08 cm EPS + 14 cm mineral fibre	4.24	2×12 floor structure insulated with 22.86 cm SPF	8.76	5.08 cm EPS II under slab with thermal break at footing and wall	1.29
2×6 frame insulated with 7.62 cm SPF + 5.08 cm XPS	4.87	2×4 roof truss insulated with 41.8 cm Blown-In	10.60	2×6 frame insulated with 10.16 cm XPS + 14 cm mineral fibre	6.38	2×12 floor structure insulated with 25.4 cm Batt	5.97	10.16 cm XTPS IV under slab with thermal break at footing and wall	3.52
2×8 frame insulated with 10.16 cm SPF + 8.89 cm Batt	5.11	2×4 roof truss insulated with 48.7 cm Blown-In	12.28	2×6 frame insulated with 14 cm mineral fibre	2.86				
2×6 frame insulated with 13.97 cm SPF + 10.16 cm EPS	7.04	2×4 roof truss insulated with 69.6 cm Blown-In	16.70						

Table 4-2 Mechanical Device Options

Hot Water Tank			Space Heating Furnace			Ventilator				
Equipment Type	**Tank Volume (L)**	**Energy Factor**	**Space Heating Type 1**	**Space Heating Type 2**	**Furnace Fan Power (W)**	**Equipment Type**	**Temperature 1 (°C)**	**Temperature 2 (°C)**	**Effiency 1**	**Effiency 2**
Condensing Tank (Vortex AO Smith, Gas)	189.3	2.50	Furnace	Air Heat Pump (Zuba Central)	302.5	EKO1.5 (Venmar)	0	–25	74	64
Tankless Water Heater (Instantaneous, Navien NPE-240A, Gas)	3.785	0.90	Furnace (Trane XR95, Gas)		125.7	HE1.8 (Venmar)	0	–25	84	72
Condensing Tank (Polaris, Gas)	189.3	0.97				Ultimate Air 200 DX	0	0	83	83
		0.95								

4.1.3 Simulation Mechanism of HOT2000

The simulation mechanism of HOT2000 is outlined in this section. For energy-efficient buildings including NZEHs, R2000 mode in HOT2000 is designated to simulate the energy consumption, in which *only space heating without cooling is simulated* (shown as grey box in Fig. 4-5). The energy requirement of a given NZEH is estimated by category of space heating, HRV, DHW heating, and base loads (including lighting, major appliances, plug outlets, exterior use, etc.). A temperature bin method with 31 temperature bins is utilized to calculate the heat loss based on mean monthly temperature. The energy simulation methods used in the old version of HOT2000 (v6) to estimate the energy consumption for space heating, DHW heating, ventilation, and base loads are described as follows.

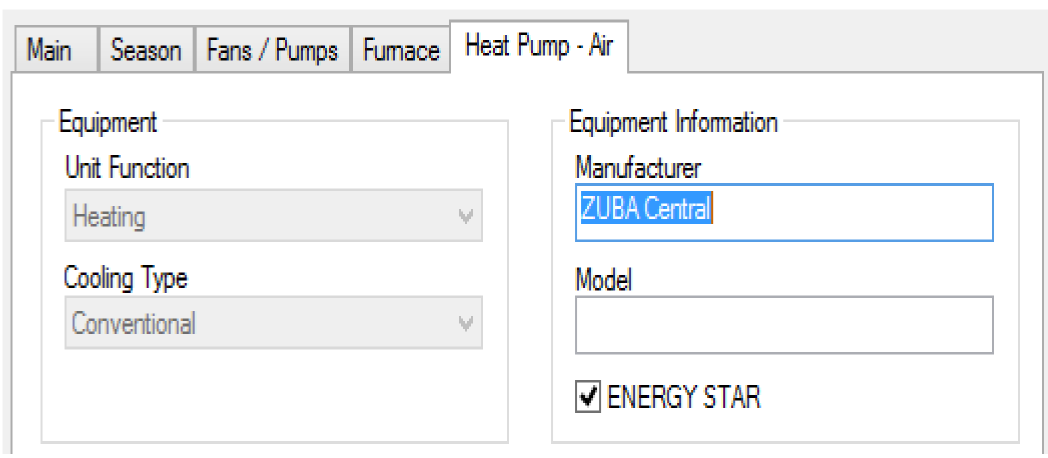


Fig. 4-5 HOT2000 Heat Pump Setting

(1) Space Heating

Energy usage for space heating is determined by the house heat balance and the coefficient of performance (COP) of equipment. The house heat balance is express as in Eq. (4-1).

$$H = L_t + L_b + L_a - n_s G_s - n_i G_i \qquad (4\text{-}1)$$

Where: H is total heat requirement for space heating; L_t is above-grade heat loss through building envelope; L_b is below-grade and foundation heat loss; L_a is heat losses due to air exchange; G_s and n_s are solar heat gain and utilization factor; $G_i$and n_i are internal heat gain and utilization factor.

After the heat losses are adjusted for heat recovery and basement heat losses, the heat loads are calculated using Eq. (4-2). Combining the heat loads and the COP of equipment, energy usage for space heating is calculated using Eq. (4-3).

$$HL = H - H_{ad} \tag{4-2}$$

$$E_{sp} = \frac{HL}{COP} \tag{4-3}$$

where HL is net heat load; H_{ad} is heat adjustment for heat recovery and basement heat losses; E_{sp} is energy usage for space heating; COP is the coefficient of performance (COP) of space heating equipment.

(2) Passive Solar Heat Gains

Passive solar heat gains are calculated based on solar radiation and glazing area, using Eq. (4-4).

$$G_s(I) = A(N) \times R(N, I) \times X(N) \times F(N) \times c \tag{4-4}$$

where $G_s(I)$ is total solar heat gains for month *I*; $A(N)$ is glazing area for orientation *N*; $R(N, I)$ is direct radiation for orientation *N* during month *I*; $X(N)$ is average transmission coefficient for orientation *N*; $F(N)$ is overhang shading factor for orientation *N*; c is solar gain coefficient.

(3) Internal Heat Gains

Internal heat gains are primarily generated from the following three sources: (1) hot water heating systems; (2) lights and appliances; and (3) occupants. The following model, expressed as Eq. (4-5), is used to estimate the internal heat gains.

$$G = G_o + G_a + G_{DHW} \tag{4-5}$$

where G is total internal heat gain; G_o is heat gain from occupants; G_a is heat gain from appliances and lighting; and G_{DHW} is heat gain from domestic hot water (DHW) system, which is calculated according to DHW heating load.

(4) Ventilation

Ventilation is utilized to improve indoor quality, and contributes two side-effects on the energy consumption: heat losses due to indoor-outdoor air exchange and energy used for system fans and heaters. The heat losses due to air exchange L_a are calculated using Eq. (4-6).

$$L_a = Q_v(I) \times D(I) \times 8.64 \times 10^{-2} \tag{4-6}$$

where $Q_v(I)$ is net ventilation heat-loss rate for month *I*, which is calculated using Eq. (4-7); $D(I)$ is days per month.

$$Q_v(I) = V_H \times \left(V_5 - \frac{V_2 \times n(I)}{100}\right) \times 1005 \times \frac{\vartheta}{3600} \times \left(T_1 - T_r(I)\right) - Q_{EF,R}(I) \times \frac{n(I)}{100} \tag{4-7}$$

where V_H is house volume; V_5 is average change rate for month *I*; V_2 is forced ventilation rate; $n(I)$ is average heat recovery ventilator efficiency for month *I*; ϑ is density of air; T_1 is temperature set-point; $T_r(I)$ is ambient temperature for month *I*; $Q_{EF,R}(I)$ is exhaust fan power averaged over month *I* when temperature is below T_1.

The monthly energy usage for preheater, supply fan, and exhaust fan is calculated as follows in Eq. (4-8) to Eq. (4-10).

$$Q_{EF,M} = \sum_{j=1}^{31} Q_{EF,j} \times hr_j \quad (4\text{-}8)$$

$$Q_{SF,M} = \sum_{j=1}^{31} Q_{SF,j} \times hr_j \quad (4\text{-}9)$$

$$Q_{H,M} = \sum_{j=1}^{31} Q_{H,j} \times hr_j \quad (4\text{-}10)$$

where $Q_{EF,M}$ is monthly energy usage of exhaust fan in month *M*; $Q_{EF,j}$ is exhaust fan power for bin *j*; $Q_{SF,M}$ is monthly energy usage of supply fan in month *M*; $Q_{SF,j}$ is supply fan power for bin *j*; $Q_{H,M}$ is monthly energy usage of preheater in month *M*; $Q_{H,j}$ is preheater power for bin *j*; *31* is constant bin number used in HOT2000 bin method; hr_j is bin hour

(5) DHW Heating

The annual energy usage for DHW heating is calculated using Eq. (4-9), based on daily hot water usage.

$$E_{DHW} = \sum_{I=1}^{12} DHW_e \times D(I) \quad (4\text{-}11)$$

where E_{DHW} is annual energy usage for DHW; DHW_e is daily energy consumption for hot water equipment; and $D(I)$ is days in month *I*.

(6) Base Loads

Base loads are used to estimate the energy consumption for lighting, major appliances, exterior use, and plug outlets etc.; the default base loads used in HOT 2000 are as follows: (1) electric appliances: 14 kWh/day; (2) lighting: 3 kWh/day; (3) exterior use: 4 kWh/day; and (4) other electricity usage (e.g., plug outlets): 3 kWh/day. The total daily base loads are estimated as 24 kWh, with the annual base loads of 8,760 kWh.

4.2 Case NZEH

A single-family NZEH, developed by Landmark in Edmonton, Canada (latitude 53°34′ N, longitude 113°31′ W), is used as the case study in this research. This NZEH is located in a cold, northern region, with extremely cold weather in winter and only a small number of hot days in summer. The 25-year average of past weather data is used in the HOT2000 simulation program, and the climate profile of the last 25 years (1990-2014), including such key parameters as heating degree days (HDDs), cooling degree days (CDDs), maximum temperature, minimum temperature, and mean temperature, is presented in Fig. 4-6 and Table 4-3. HDDs is the sum of the number of degrees Celsius that the mean temperature is below 18 °C of given days, and CDDs is the sum of the number of degrees Celsius that the mean temperature is above 18 °C of given days (Environment Canada 2015). The HDDs and CDDs are used primarily to estimate the heating and cooling requirements of buildings. Due to the cold weather, space heating comprises one of the challenges for the NZEH design.

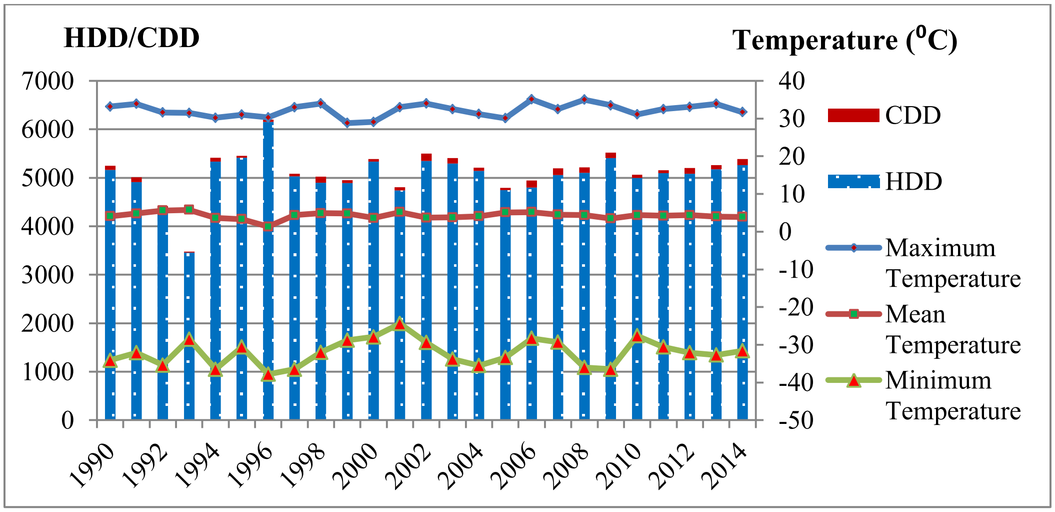


Fig. 4-6. Weather Profile for the Period, 1990-2014

Table 4-3 Edmonton 25-year Climate Profile (1990-2014)*

Year	Heating Degree Days (HDDs)	Cooling Degree Days (CDDs)	Temperature		
			Maximum	Mean	Minimum
1990	5,159.7	87.7	33.2	4.1	–34.1
1991	4,914.6	94.3	33.9	4.8	–32.1
1992	4,346.5	69.6	31.6	5.6	–35.4
1993	3,458.9	19.4	31.5	5.8	–28.5
1994	5,336.0	78.2	30.2	3.6	–36.5
1995	5,411.9	39.4	31.0	3.3	–30.6
1996	6,152.1	46.8	30.3	1.3	–37.8
1997	5,028.7	54.5	33.0	4.4	–36.5
1998	4,900.9	124.0	34.0	4.9	–32.0
1999	4,892.8	58.5	28.8	4.8	–28.8
2000	5,334.9	55.9	29.1	3.6	–27.9
2001	4,740.0	69.3	33.0	5.2	–24.4
2002	5,351.2	146.2	34.0	3.7	–29.4
2003	5,294.4	109.9	32.5	3.8	–33.8
2004	5,143.8	67.0	31.2	4.1	–35.5
2005	4,749.4	45.5	30.1	5.1	–33.4
2006	4,802.2	143.4	35.1	5.2	–28.3
2007	5,055.6	139.4	32.5	4.5	–29.3
2008	5,102.8	115.0	35.0	4.4	–36.0
2009	5,406.6	111.5	33.5	3.5	–36.5
2010	5,000.7	61.2	31.1	4.4	–27.6
2011	5,097.2	55.8	32.5	4.2	–30.6
2012	5,080.8	120.8	33.1	4.4	–32.1
2013	5,177.2	83.0	33.9	4.0	–32.7
2014	5,263.7	126.4	31.7	3.9	–31.6

* Source Data: http://edmonton.weatherstats.ca/metrics/hdd.html

The building is east-oriented with a south-facing roof, as pictured in Fig. 4-7. The fundamental characteristics of the NZEH design are as follows: (1) high performance insulation is applied to such building envelope as main wall, roof, exposed floor, and basement wall, and the basement floor is insulated as well; (2) triple-glazed windows are used with different *R*-Values for different orientations (lower values for south-facing windows and higher values for other orientations) to utilize passive solar gain in cold seasons, and sun-stop film is applied on the west-facing windows to mitigate the solar side-effects in summer; (3) heat pump technology is utilized for space heating and hot water heating, and heat recovery is used for ventilation and drain water; and (4) a 12.936 kW roof-mounted and grid-connected solar PV system is employed as the only energy generation approach in this case. The initial building design information of this NZEH case is summarized in Table 4-4, while the schematic diagram of energy flow is demonstrated in Fig. 4-8. The estimated energy consumption of the design scenario is 69,940 MJ annually.

The floor plans of the NZEH are displayed in Fig. 4-9 and Fig. 4-10. This case NZEH was built using an off-site construction method, panelized construction. The wall and floor panels were manufactured in a prefabrication facility with spray foam insulation; after the prefabricated panels were transported to the site, the NZEH was assembled on-site for the framing phase. The construction process after framing is similar to the conventional construction method. The panelized construction process of this NZEH is demonstrated in Fig. 4-11 to Fig. 4-14. The air-blow test indicates that the NZEH has an air-tightness of 0.57 ACH; in other words, the NZEH was air-tightly built with high construction quality.

Fig. 4-7. NZEH Case: Front (East Facing)

Table 4-4 Initial Design Information for Case NZEH

General Building Information		**Building Envelope**	
Builder	Landmark Homes	**Main Wall**	2×8 framed 24″ o/c, insulated with 12.7 cm spray foam and 6.73 cm spray fiberglass
Building type	Single-Family Home	**Attic**	2×4 roof truss insulated with 8.89 cm SPF + 41.8 cm blown-in
Building orientation	East-facing	**Basement Wall**	2×4 frame with drywall insulated with 8.89 cm Batt + 8.89 cm SPF
Gross Floor Area	222 m^2	**Basement Slab**	10.16 cm EPS II under slab with thermal break at footing and wall
Year completed	2013	**Window type**	South-facing: triple-glazed glass with single low-e argon Others: triple-glazed glass, two panes with sun stop coating and argon
Certification	Energy Guide 100	**Exposed Floor**	2×12 floor structure insulated with 17.78 cm SPF
Annual heating degree days	5,589	**Window U-Value**	South-facing 0.184, All other directional orientations 0.124
Latitude	53.403°	**Air tightness**	0.57 ACH50
Thermal conductance of building envelope	90.7 W/K	**Thermal conductance due to air exchange**	Mechanical ventilation: 25.1 W/K; Infiltration: 32.4 W/K

Other Information		MEP Systems	
Estimated annual energy use	69,940 MJ	**Space heating**	ZUBA Central Air source heat pump with electric resistance heater as backup
Modelled annual heating load	42,523.3 MJ	**Ventilation**	Venmar EKO 1.5 Ultra-Efficient HRV
Electrical Generation	grid-connected, 12.936 kW solar PV system	**Water heating**	AO Smith Voltex Air source heat pump hot water tank (80 gallon) + Drain-water heat recovery system

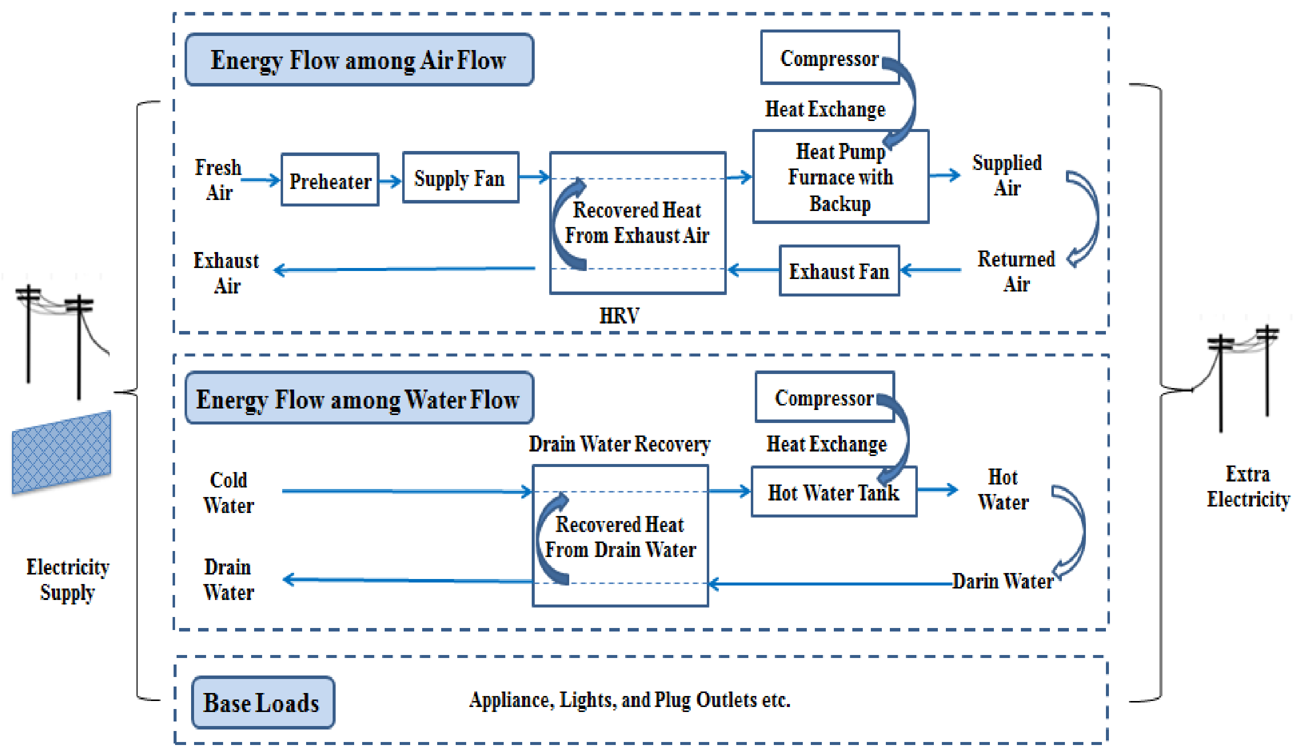


Fig. 4-8. Schematic Diagram of Energy Flow

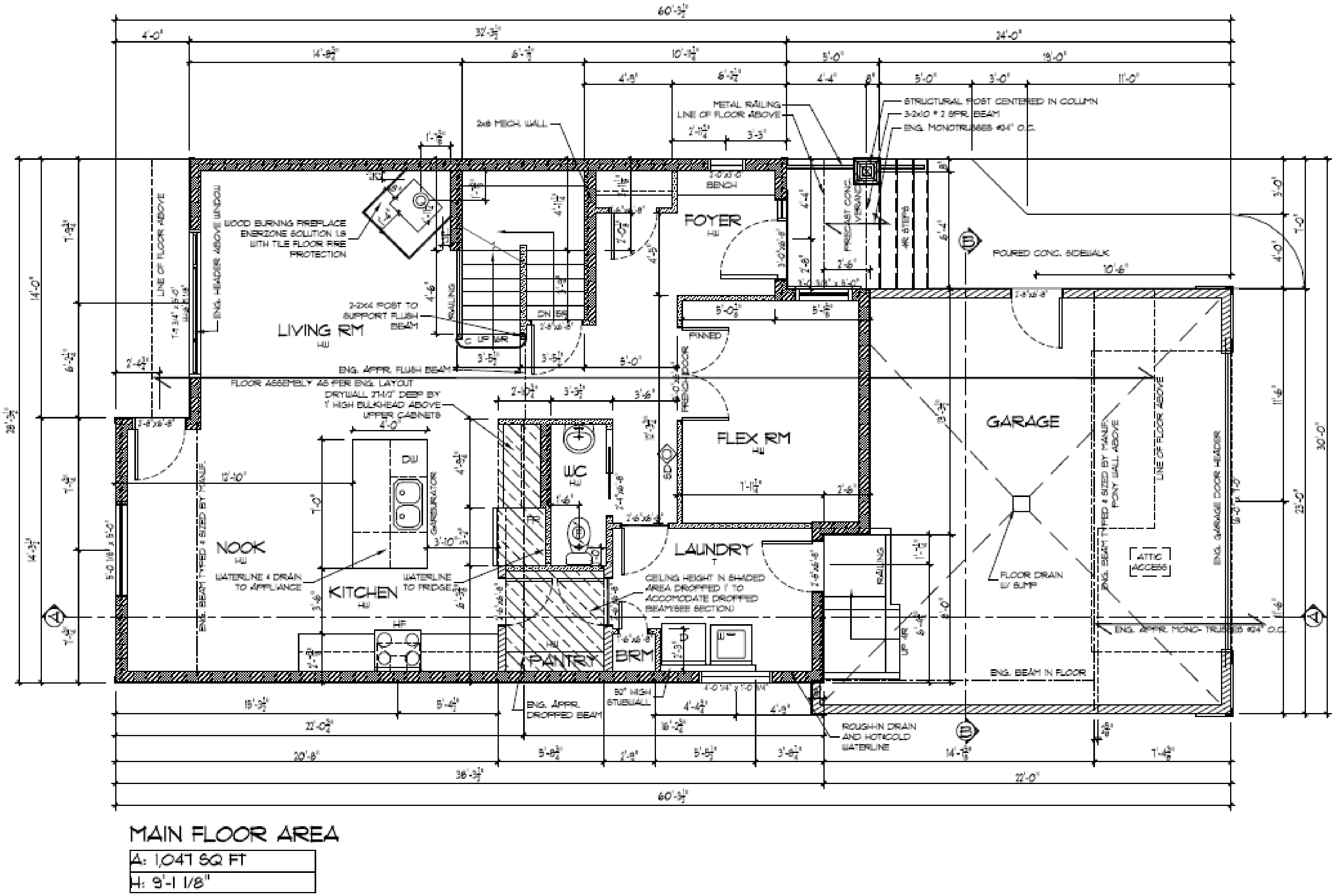


Fig. 4-9. First Floor Plan

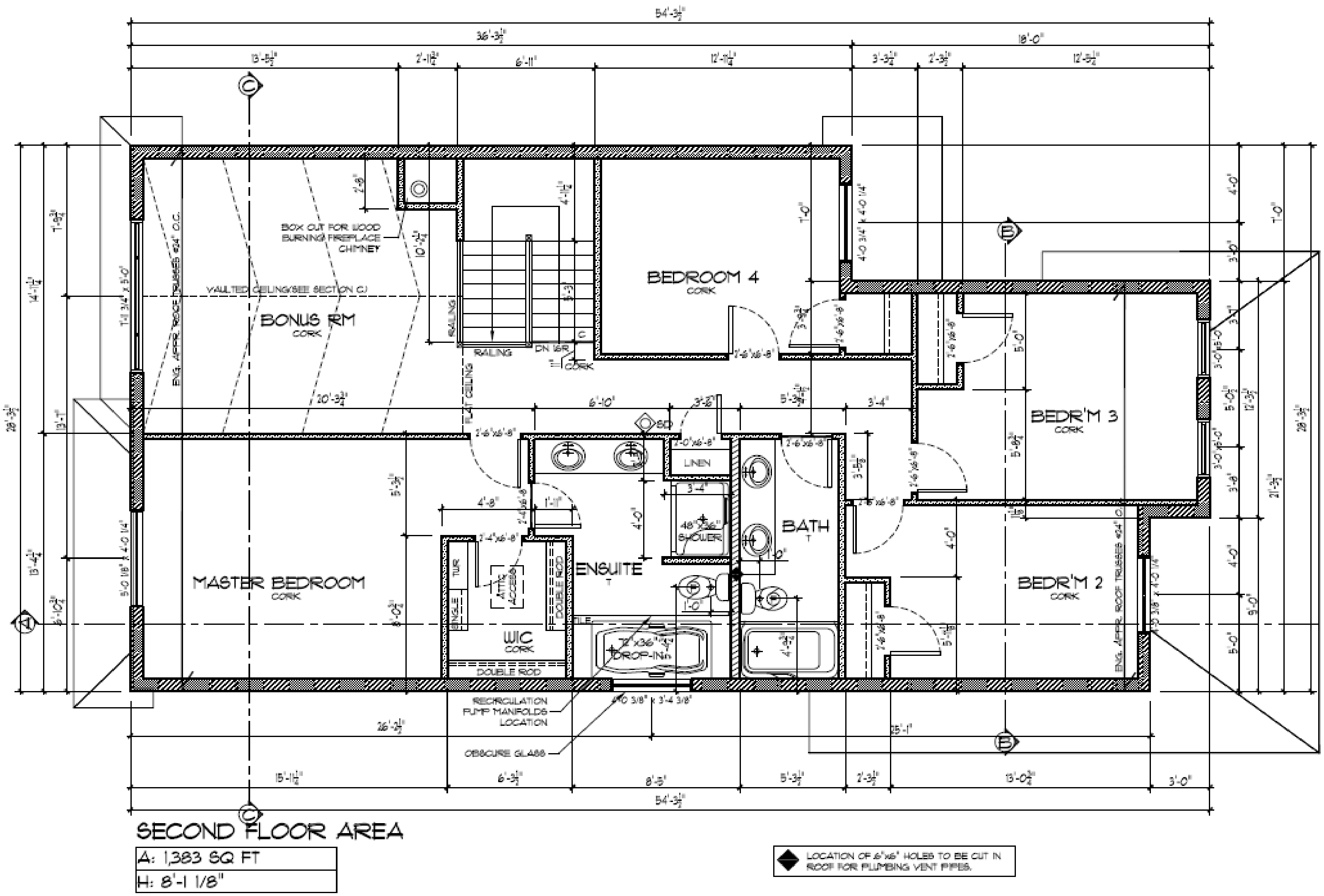


Fig. 4-10. Second Floor Plan

Fig. 4-11. Panel Manufacturing

Fig. 4-12. Spray Foam

Fig. 4-13. Panel Transportation

Fig. 4-14. Panel Erection

4.3 Single-Factor Simulation and Analysis

To identify the impacts of different design options on the energy performance of NZEHs individually, single-factor simulation is conducted for the NZEH. The annual energy consumption is simulated for the design options of the building envelope and mechanical system, which is listed above, using the Batch Version HOT2000; based on the simulation results, curve-fitting is applied for such numerical variables as main wall, roof, exposed floor, basement wall, and basement floor as follows.

(1) Main Wall: Five practical design options for the main wall, listed in Table 4-1, are simulated to identify the impacts on the annual energy consumption, while other parameters are kept the same as in the initial design. The simulation results are displayed in Table 4-5, and curve-fitted as expressed in Fig. 4-15, in which the energy performance of main wall options is quantitatively illustrated.

Table 4-5 Simulation Result: Main Wall

RSI Value (K•m^2/W)	Energy Consumption (MJ)
4.22	70,304
4.87	68,282
5.11	67,933
6.25	66,479
7.04	65,540

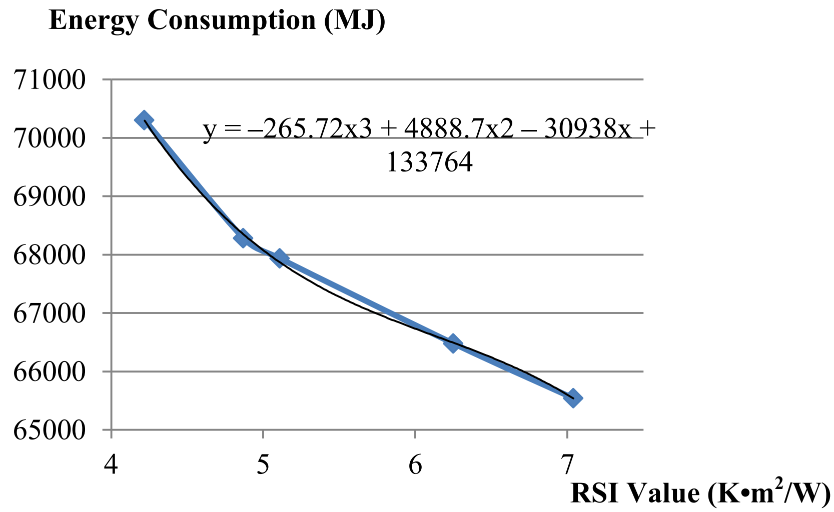


Fig. 4-15. Energy Performance: Main Wall

(2) Roof: Five practical design options for the roof, listed in Table 4-1, are simulated to identify the impacts on the annual energy consumption, and other parameters are kept the same as in the initial design. The simulation results are presented in Table 4-6, and curve-fitted as observed in Fig. 4-16, in which the energy performance of roof options is quantitatively demonstrated.

Table 4-6 Simulation Result: Roof

RSI Value (K•m^2/W)	Energy Consumption (MJ)
8.85	67,368

10.60	66,957
12.28	66,723
13.81	66,505
16.70	66,253

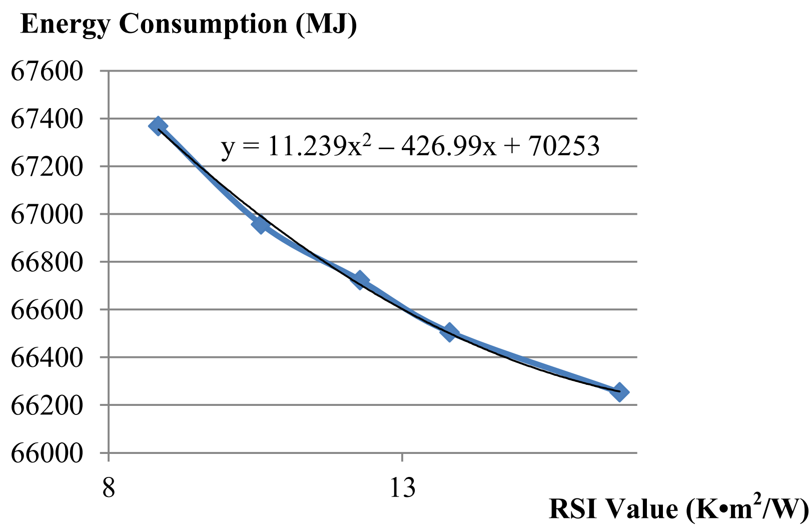


Fig. 4-16. Energy Performance: Roof

(3) Exposed Floor: Three practical design options for the roof, listed in Table 4-1, are simulated to find the impacts on the annual energy consumption, while other parameters are kept the same as in the initial design. The simulation results are expressed in Table 4-7, and curve-fitted as observed in Fig. 4-17, in which the energy performance of exposed floor options is quantitatively displayed.

Table 4-7 Simulation Result: Exposed Floor

RSI Value ($K \cdot m^2/W$)	Energy Consumption (MJ)
5.97	66,728
7.31	66,506
8.76	66,372

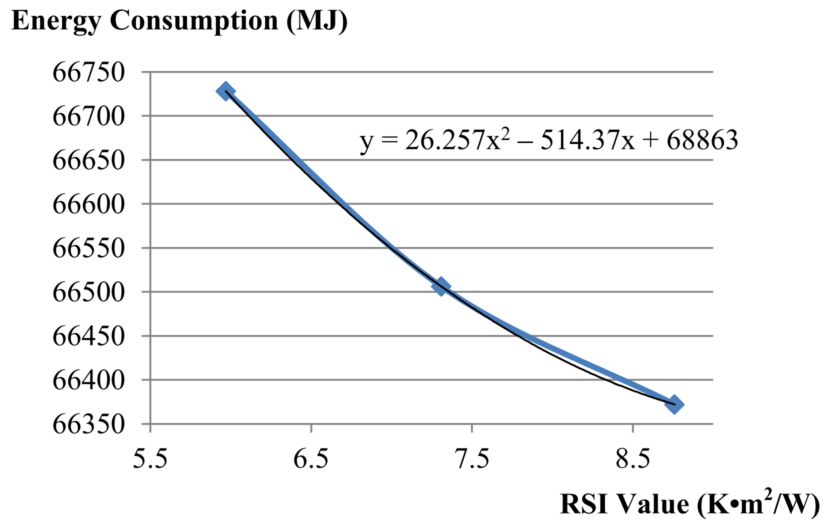


Fig. 4-17. Energy Performance: Exposed Floor

(4) Basement Wall: Four practical design options for the basement wall, listed in Table 4-1, are simulated to find the impacts on the annual energy consumption, while other parameters are kept the same as in the initial design. The simulation results are provided in Table 4-8, and curve-fitted as demonstrated in Fig. 4-18, in which the energy performance of basement wall options is quantitatively displayed.

Table 4-8 Simulation Result: Basement Wall

RSI Value ($K \cdot m^2/W$)	Energy Consumption (MJ)
2.86	67,984
4.24	67,020
5.51	66,505
6.38	66,254

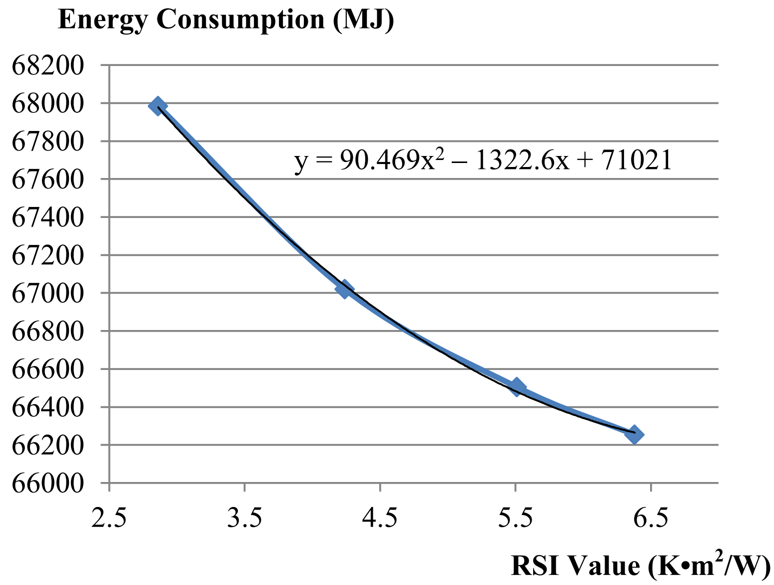


Fig. 4-18. Energy Performance: Basement Wall

(5) Basement Floor: Three practical design options for the roof, listed in Table 4-1, are simulated to highlight the impacts on the annual energy consumption, while other parameters are kept the same as in the initial design. The simulation results are presented in Table 4-9, and curve-fitted as shown in Fig. 4-19, in which the energy performance of basement floor options is quantitatively demonstrated.

Table 4-9 Simulation Result: Basement Floor

RSI Value ($K•m^2/W$)	Energy Consumption (MJ)
1.29	66,562
2.57	66,505
3.52	66,465

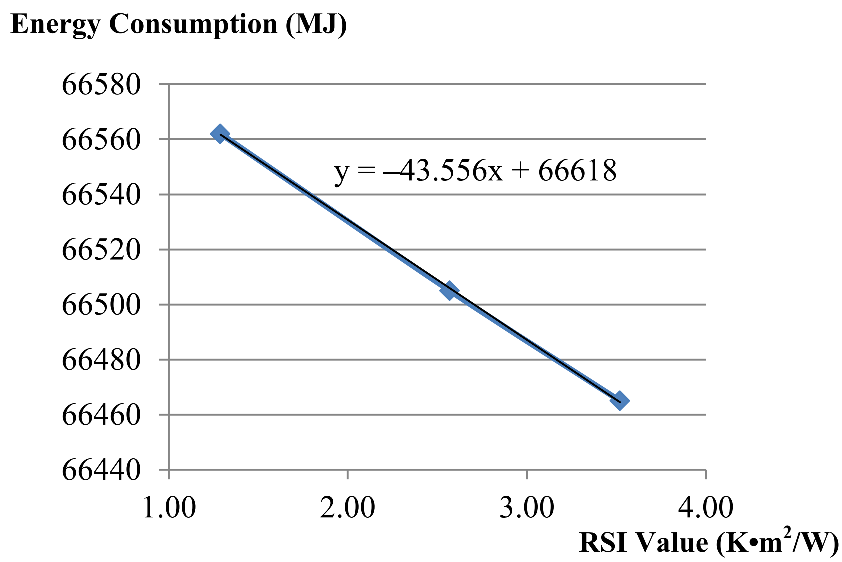


Fig. 4-19. Energy Performance: Basement Floor

(6) Space Heating: Two practical design options for the space heating furnace, listed in Table 4-2, are simulated individually, and other parameters are kept the same as in the initial design; the estimated annual energy consumption for the two design options is displayed in Table 4-10.

Table 4-10 Simulation Result: Space Heating

Space Heating Type 1	Space Heating Type 2	Energy Consumption (MJ)
Furnace	Air Heat Pump (Zuba Central)	66,505
Furnace (Trane XR95, Gas)		84,742

(7) DHW Heating: Three practical design options for the DHW tank, listed in Table 4-2, are simulated in this section, while other parameters are kept the same as in the initial design; the estimated annual energy consumption for the three design options is demonstrated in Table 4-11.

Table 4-11 Simulation Result: DHW Heating

DHW Tank	Energy Consumption (MJ)
Condensing Tank (Vortex AO Smith, Gas)	67,271
Tankless Water Heater (Instantaneous, Navien NPE-240A, Gas)	66,220
Condensing Tank (Polaris, Gas)	66,505

(8) Ventilation: Three practical design options for the HRV, listed in Table 4-2, are simulated individually, while other parameters are kept the same as in the initial design; the estimated annual energy consumption for the three design options is shown in Table 4-12.

Table 4-12 Simulation Result: HRV

HRV	Energy Consumption (MJ)
EKO1.5 (Venmar)	66,505
HE1.8 (Venmar)	64,719
Ultimate Air 200 DX	64,295

The results of single-factor simulation provide initial information with regard to the individual factor for NZEH design. To have complete information, the combinations of building envelope and mechanical system design options are simulated for this NZEH case as follows.

4.4 Multiple-Factor Simulation and Analysis

The combinations of the design options listed in Table 4-1 and Table 4-2 are simulated as the design scenarios for the NZEH case in this section. The design options of building envelope are simulated as numerical variables, with insulation RSI as the values, and the mechanical component options are simulated as categorical variables, with the specifications as the inputs. With the template of a pair of V71 & V80 files updated for each iteration (one combination of design options) per run, in total 16,200 design scenarios (combinations of design options listed in Table 4-1 and Table 4-2) are simulated for this NZEH case, and the results are analyzed as follows.

4.4.1 Simulation Results and the Profiles

The simulation results (16,200 in total) are plotted with regard to each factor to present the energy profiles from different views, which are demonstrated as follows.

(1) Space Heating: A conventional natural gas furnace and a heat pump electric furnace with a conventional electric furnace as backup are simulated in this research. The overall energy consumption profile of 16,200 design scenarios with regard to space heating type is plotted as Fig. 4-20. The total energy consumption is clustered by two types of space heating equipment: (1) heat pump equipment brings in an annual total energy usage between 62,365 MJ and 74,137 MJ, and the specific amount depends on other simulation factor values. (2) If using a conventional natural gas furnace, the annual total energy consumption ranges between 77,171 MJ and 99,604 MJ. The pattern is periodic in nature corresponding to the design options of main wall, which is the first factor simulated in this research.

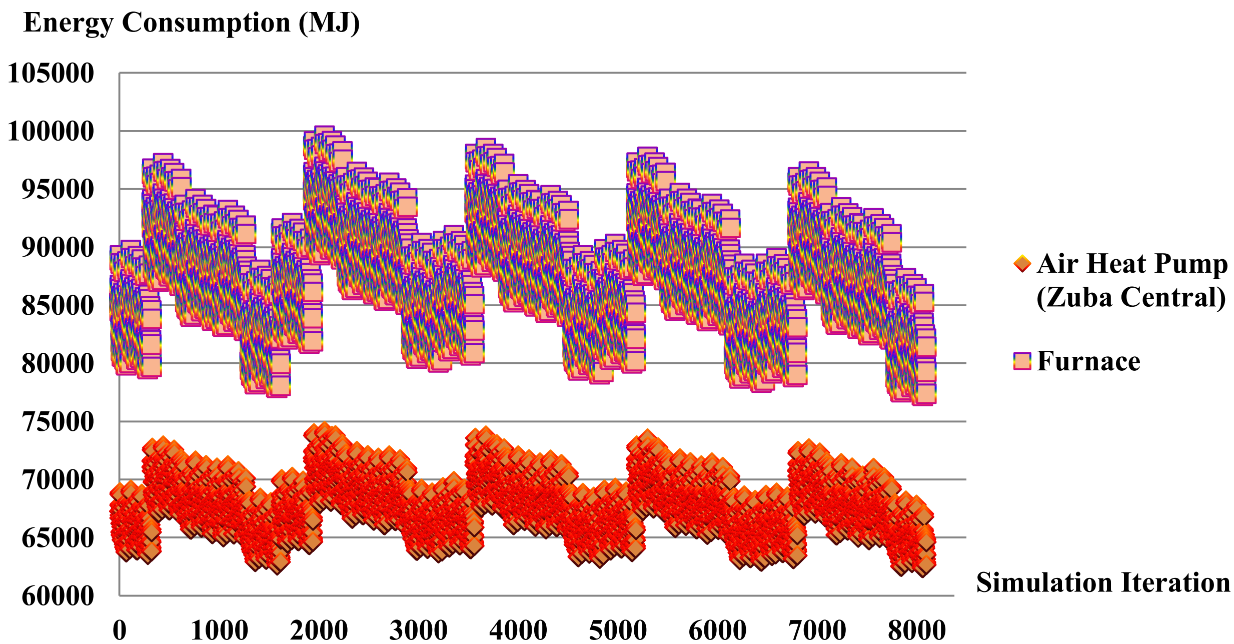


Fig. 4-20. Energy Consumption Profile: Space Heating

(2) Hot Water Heating: The overall energy consumption profile is plotted from the view of three types of hot water tanks, as demonstrated in Fig. 4-21. From Fig. 4-21, it can be observed that the energy consumption of different hot water tanks overlap with one another, which means that using different hot water tanks does not yield a significant change in the total energy consumption. Meanwhile, the specific energy consumption depends on other simulation factors' values. From Fig. 4-21 it also can be observed that the total energy consumption is largely clustered into two groups, which have the same energy consumption ranges as different space heating types; therefore, space heating is found to be the main clustering factor with regard to the total energy consumption.

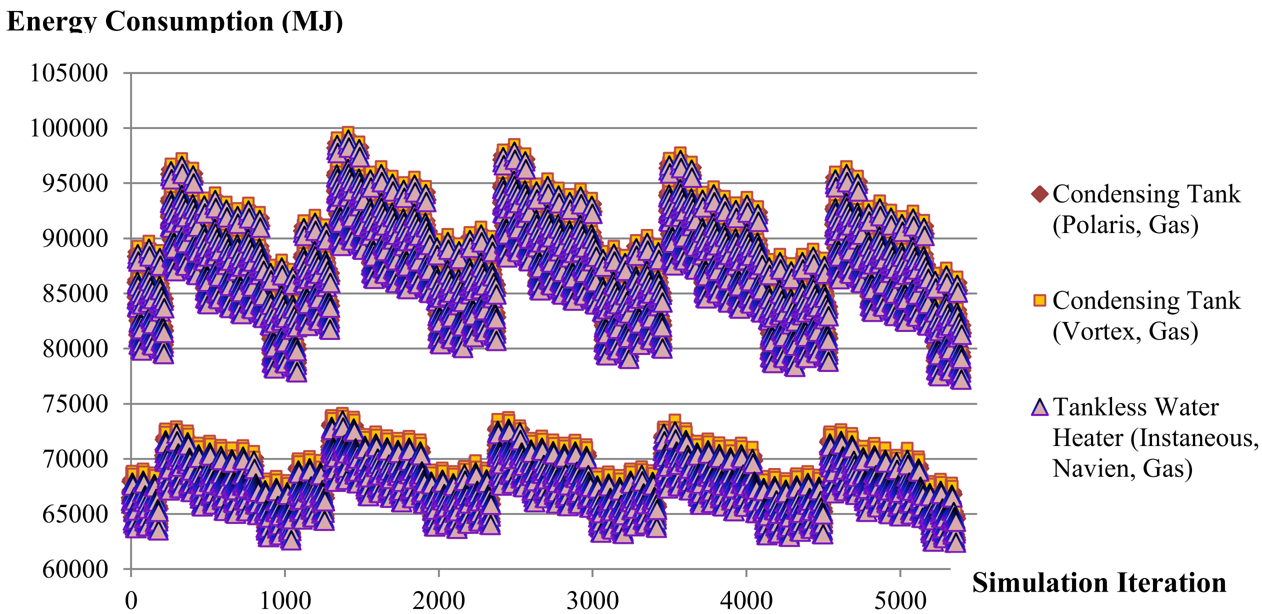


Fig. 4-21. Energy Consumption Profile: Hot Water Heating

(3) Main Wall: The overall energy consumption profile is plotted from the view of five practical design options for the main wall, as illustrated in Fig. 4-22. It can also be observed that the total energy consumption is primarily clustered by space heating equipment, and the specific energy consumption amount depends on other factor values as well.

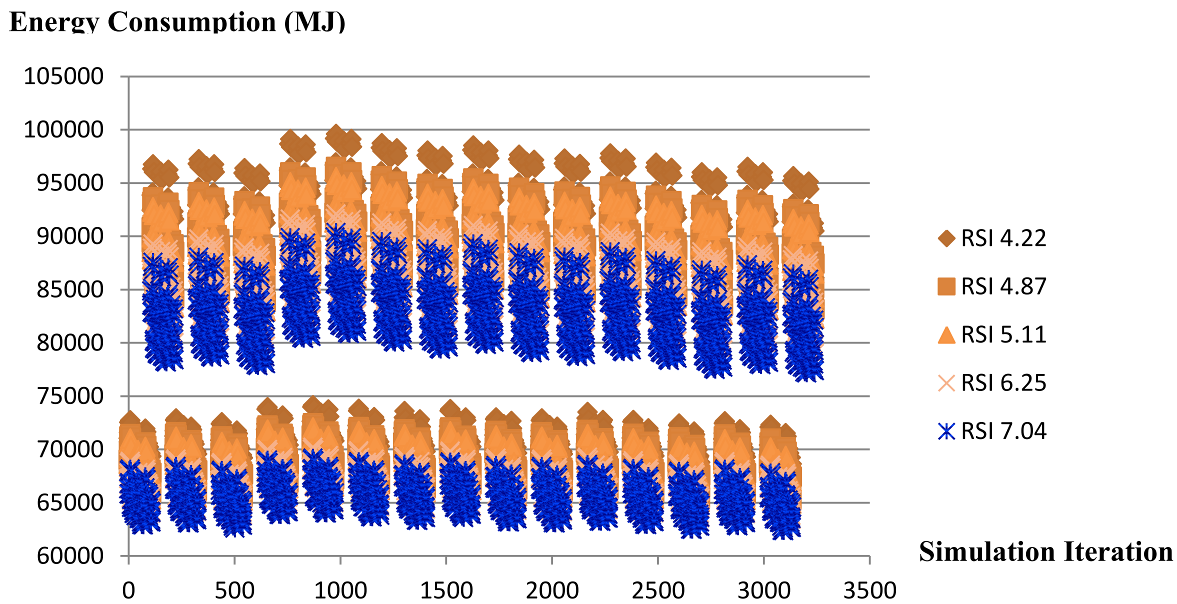


Fig. 4-22. Energy Consumption Profile: Main Wall

The total energy consumption profiles from the view of HRV, exposed floor, roof, basement wall, and basement slab have similar patterns to the main wall, and are clustered mainly by space heating equipment type. Based on the simulation results, the following potential knowledge can be identified for NZEH design: (1) factor importance ranking: through the factor importance ranking, the overall factor influence can be investigated and ranked for NZEH design, which reflects the factor sensitivity with regard to the energy consumption; (2) regression analysis: regression models will formulate the energy consumption with the building envelope and mechanical device variables, and provide a higher level of knowledge than that offered by technology suites for NZEH design.

4.4.2 Regression Analysis

In order to formulate the energy consumption with the design options of main wall, roof, exposed floor, basement wall, basement floor, space heating, hot water heating, and HRV, such data regression approaches as linear regression and neural network are employed for modelling purposes in this chapter. Among the simulated factors, space heating, hot water heating, and HRV are applied as categorical variables; while main wall, roof, exposed floor, basement wall, and basement floor are modelled as numerical factors with RSI values as the variables.

(1) Linear Regression

Linear regression fits a data model that is linear in the model *coefficients* (parameters), with this data having normally distributed errors. A regression model defines the distribution of a *response variable* (y) in terms of *predictor variables* (x_1, x_2, ...). The ordinary linear regression models y as a normal random variable, with the mean as a linear function of the predictors, and the variance remains constant (Robert 2014; Drape 2014). A linear regression model that contains more than one predictor variable, as in Eq. (4-12), is called a *multiple linear regression model*.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \varepsilon \tag{4-12}$$

where Y is the response variable; x_1, x_2, ... are predictor variables; β_0 is the intercept of a plane in the n-dimensional space; β_1, β_2, ... are *regression coefficients* (for example, β_1 represents the change in the mean value of response corresponding to a unit change in x_1 while other variables remain unchanged); ε is random error.

A linear regression model may take the following form:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \cdots + \varepsilon \tag{4-13}$$

where $x_1 x_2$ is a cross-product term of x_1 and x_2, which represents an **interaction effect** between the two variables; interaction means that the effect produced by a change in the predictor variable on the response *depends on* the level of the other predictor variable(s).

In some cases, linear regression is expressed using Wilkinson notation, which corresponds to Standard Notation as in Table 4-13 (Wilkinson 1973).

Table 4-13 Wilkinson Notation Interpretation

Wilkinson notation	Factors in standard notation
1	Constant (intercept) term
A^k, where k is a positive integer	A, A^2, ..., A^k
A + B	A, B
A*B	A, B, A*B
A:B	A*B only
−B	Do not include B
A*B + C	A, B, C, A*B
A + B + C + A:B	A, B, C, A*B
A*B*C − A:B:C	A, B, C, A*B, A*C, B*C
A*(B + C)	A, B, C, A*B, A*C

Least-Square fit and stepwise regression are the typical regression methods for linear regression. Least-Square fit is a popular method used to fit linear regression models; however, model form (equation form) is required for Least-Square fit, which means Least-Square fit is parameter-fitting only. For an uncertain model, stepwise is a sound method to fit a linear regression model.

The coefficient of determination (R^2) measures the goodness of fit. This statistic explains how closely values obtained from a fitted model match the dependent variable, by way of indicating the proportionate amount of variation in the response variable, y, which is explained by the independent variables, x, in the linear regression model. The larger the R^2 value, the greater the extent to which variability is explained by the linear regression model. R^2 is calculated in Eq. (4-14) to Eq. (4-16).

$$SST = \sum(y_i - \bar{y})^2 \tag{4-14}$$

$$SSE = \sum(y_i - \hat{y}_i)^2 \tag{4-15}$$

$$R^2 = 1 - \frac{SSE}{SST} \tag{4-16}$$

where y_i is the observed response value; $\bar{y}$ is the average observed response value; $\hat{y}_i$ is the fitted response value; SSE is the sum of squared error; SSR is the sum of squared regression; SST is the sum of squared total, also expressed as a regression identity.

With the linear regression and the Least-Square fit method applied on the simulation results, a general linear regression model is proposed for the NZEH case in Wilkinson notation format, as displayed in Eq. (4-17). The estimated coefficients and statistical parameters are listed in Table 4-14. The model performance of estimated energy consumption versus actual energy consumption is illustrated in Fig. 4-23, and error over estimated energy consumption is shown in Fig. 4-24.

$$y \sim 1 + x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 \tag{4-17}$$

where y is estimated energy consumption; x_1 is the R-value of the attic; x_2 is the R-value of the main wall; x_3 is the R-value of the exposed floor; x_4 is the R-value of the basement slab; x_5 is the R-value of the basement wall; x_6 is the categorical variable of space heating, with 1 representing conventional natural gas furnace/specification and 2 referring to the heat pump furnace/specification; x_7 is the categorical variable of hot water heating, with 1, 2, and 3 representing the three types of hot water tank and the corresponding specifications; x_8 is the categorical variable of HRV, with 1, 2, and 3 representing the three types of HRV and the corresponding specifications.

Table 4-14 Estimated Coefficients and Statistical Parameters

	Estimate	Squared Error (SE)	tStat (Estimate/SE)	pVal
Intercept	92,293.00	103.80	889.17	0
x_1	−269.04	3.55	−75.82	0
x_2	−2,330.40	9.48	−245.87	0
x_3	−220.50	8.40	−26.25	2.198e-148
x_4	−133.74	10.49	−12.74	5.278e-37
x_5	−928.98	7.19	−129.13	0
x_{6_2}	19,407.00	19.15	1,013.60	0
x_{7_2}	−855.27	23.43	−36.50	2.961e-279
x_{7_3}	−607.43	23.48	−25.87	2.424e-144
x_{8_2}	−2,551.40	23.48	−108.59	0
x_{8_3}	−3,100.60	23.40	−132.51	0

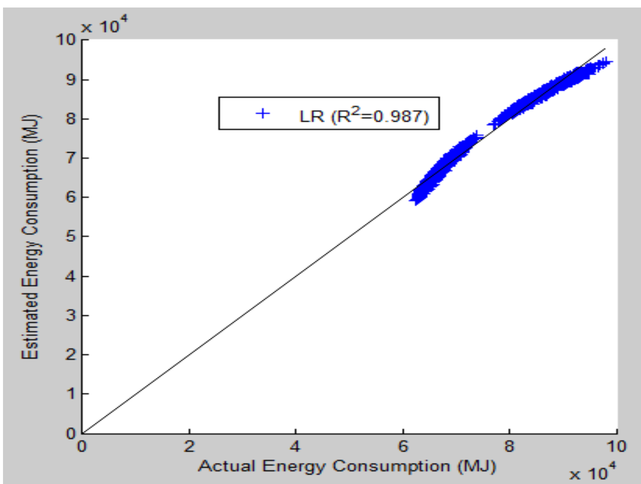


Fig. 4-23. Estimated versus Actual Energy Consumption

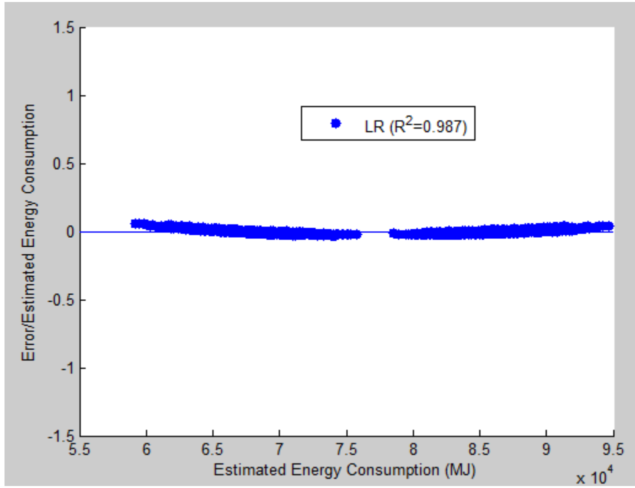


Fig. 4-24. Error/Estimated Energy Consumption

(2) Neural Network

Neural Network (NN) is a machine learning method that mimics the human neural system to perform computational modelling or pattern recognition. NN is a system of interconnected "neurons", which have the ability to compute values from inputs. NN includes input layer, hidden layer, and output layer; input information is transferred by a transfer function, and trained by a training algorithm. Transfer functions are used to map or scale input and output in order to enhance or simplify NN performance. The model is approximated by using such algorithms as the Levenberg–Marquardt algorithm (LMA), the BFGS Quasi-Newton, and the Scaled Conjugate Gradient. In this research, a sigmoid function is used for hidden layers, expressed as Eq. (4-18), while a linear function is used for the output layer, since these functions have been verified to have optimal performance compared to others. LMA is the best applicable algorithm for regression issues in terms of accuracy and speed (Stergiou and Siganos 2014;

Moré 1977), and is thus applied in this research. The NN methodology applied in this research is illustrated in Fig. 4-25.

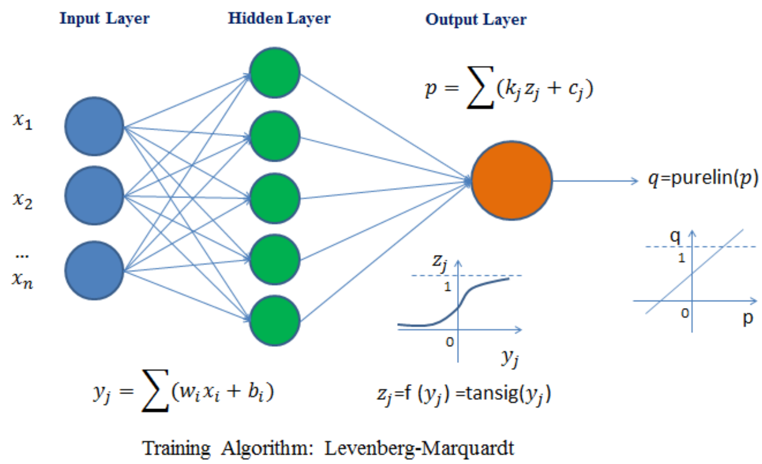


Fig. 4-25. Neural Network Methodology

$$tansig(x) = \frac{2}{(1+e^{-2x})} - 1 \tag{4-18}$$

where x is the input of the sigmoid function.

LMA, also known as the damped least-squares (DLS) method, is used to solve non-linear least square problems. The principle underlying LMA is as follows: given a set of empirical datum pairs of independent and dependent variables, (x_i, y_i), optimize the parameters w of the model f(x, w) to minimize the sum of the squares of the deviations (Moré 1977):

$$S(w) = \sum_{i=1}^{m} [y_i - f(x_i, w)]^2 \tag{4-19}$$

where $S(w)$ is the sum of squared deviations; x_i represents the independent variables; and y_i represents the dependent variables.

LMA is applied in an iterative procedure. In each iteration, the parameter vector, w, is replaced by a new estimate, $w + \delta$, which is approximated using Eq. (4-24) to Eq. (4-22).

$$f(x_i, w + \sigma) \approx f(x_i, w) + J_i\delta \tag{4-20}$$

$$J_i = \frac{\partial f(x_i, w)}{\partial w} \tag{4-21}$$

$$S(w + \delta) \approx \sum_{i=1}^{m} [y_i - f(x_i, w) - J_i\delta]^2 \tag{4-22}$$

Levenberg's contribution is to replace this equation by a "damped version" to control the reduction of the sum of squared deviations, *S(w)* in each iteration, as shown in Eq. (4-23):

$$(J^T J + \gamma I)\delta = J^T[y - f(w)] \tag{4-23}$$

where J is the Jacobian matrix whose i^{th} row equals J_i; J_i is the gradient of $f(x_i, w)$ with respect to w; f is the vector with the i^{th} component as $f(x_i, w)$; and y is the vector with i^{th} component y_i. γ is the damping factor.

NN modelling is applied for the NZEH case, with the schematic diagram of NN demonstrated in Fig. 4-26. The NN includes eight input variables, a hidden layer with 10 nodes, an output layer with one node, and an output. The fitted model parameters are presented in Table 4-15 and Table 4-16. The network performance in terms of Mean-Squared Error (MSE) and *R*-value is displayed in Fig. 4-27 and Fig. 4-28.

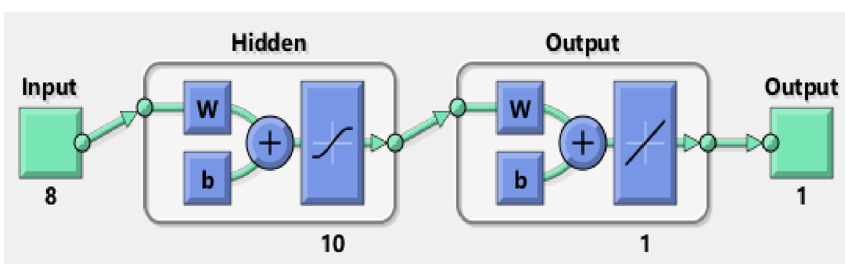


Fig. 4-26. Network Schematic Diagram

Table 4-15 Input Weight Matrix: Hidden Layer

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	b_1
Node1	0.00015	–0.02306	–0.00103	–0.05552	–0.61482	0.22821	0.00055	0.01072	–1.8157
Node2	–0.00434	–0.00814	–0.00571	–0.00104	–0.01461	0.36947	0.00095	–0.89930	–1.7923
Node3	0.12919	0.06366	–1.69101	0.01771	0.03687	–0.56802	0.05569	0.13763	1.5954
Node4	–0.00126	0.53685	0.00042	0.00025	0.00259	–0.20947	0.00034	0.01058	1.6263
Node5	0.01689	0.05377	0.01483	0.00232	0.02752	1.11311	–0.21216	–0.02714	–0.5126
Node6	–0.57106	–0.01232	–0.00250	–0.00107	–0.00757	0.24362	0.00319	–0.00474	–2.0638
Node7	0.01348	0.03672	0.01171	0.00178	0.02160	1.84055	0.13188	–0.02159	–1.1835
Node8	–0.01583	–0.07615	–0.01116	–0.00005	–0.01548	–2.72097	1.67619	0.04781	–1.4613
Node9	–0.01458	–0.05373	–0.01294	–0.00195	–0.02540	1.35598	0.00833	–0.03073	0.1966
Node10	2.44398	2.56718	1.42746	–0.19914	2.57610	–1.17776	0.17136	–0.08097	4.5883

where $\boldsymbol{x_1}$ is the *R*-value of the attic; $\boldsymbol{x_2}$ is the *R*-value of the main wall; $\boldsymbol{x_3}$ is the *R*-value of the exposed floor; $\boldsymbol{x_4}$ is the *R*-value of the basement slab; $\boldsymbol{x_5}$ is the *R*-value of the basement wall; $\boldsymbol{x_6}$ is the categorical variable of space heating; $\boldsymbol{x_7}$ is the categorical variable of hot water heating; $\mathbf{x_8}$ is the categorical variable of HRV; $\mathbf{b_1}$ is the intercept for each node of the hidden layer.

Table 4-16 Input Weight Matrix: Output Layer

	Node1	**Node2**	**Node3**	**Node4**	**Node5**	**Node6**	**Node7**	**Node8**	**Node9**	**Node10**
W	0.5960	0.5170	–0.0071	–1.146	–0.8230	0.74431	–1.6009	–0.0730	2.5342	–0.00025
$\mathbf{b_2}$	1.884									

where **W** is the weight for each node of the output layer; and $\mathbf{b_2}$ is the intercept of the output layer.

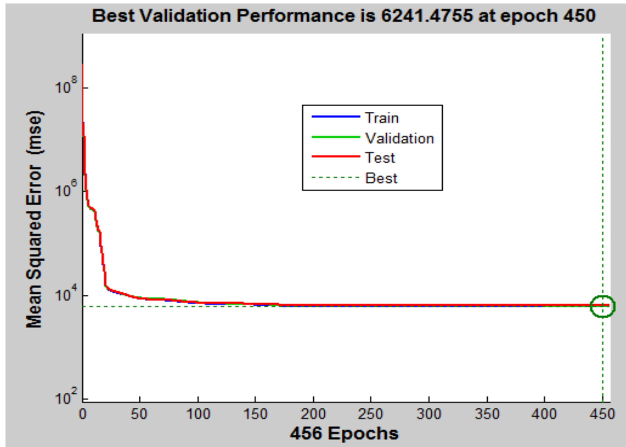


Fig. 4-27. Neural Network Performance: MSE

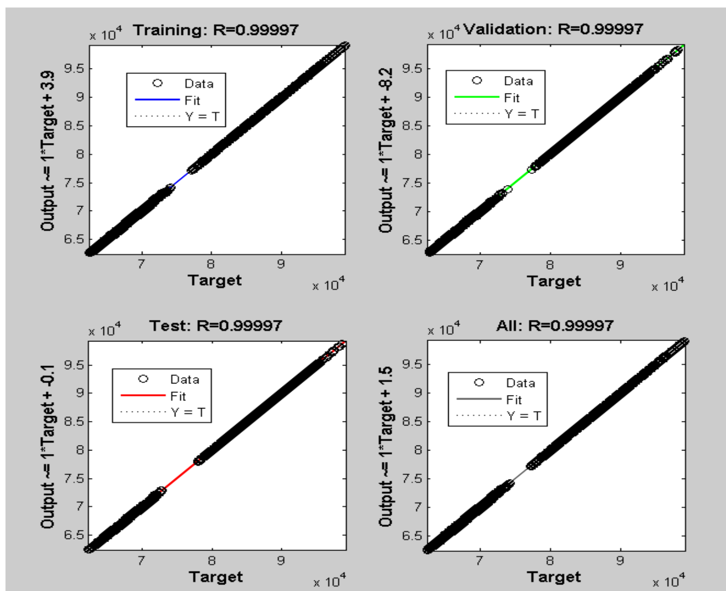


Fig. 4-28. Neural Network Performance: R Value

The regression models provide a higher level of knowledge than do technical suites, which are commonly recommended for NZEH design. These regression models are less complicated than original energy simulation methodologies to describe the energy consumption of different design scenarios for NZEH design.

Additionally, occupant behaviour exerts impacts on the energy performance of NZEHs, among which the temperature set-point is a formative factor for space heating and could be investigated by way of a simulation approach; thus, the energy usage for space heating is simulated and analyzed with regard to different temperature set-points in this research as follows.

4.4.3 Factor Importance Analysis based on Regression Tree

For the mixed numerical and categorical factors, the algorithm of factor importance ranking based on regression tree splits has been shown to be effective for the simulation results in our research. A data mining decision tree is categorized into classification decision tree and regression decision tree, corresponding to different response types. Breiman et al. (1984) have introduced both the classification and regression trees systematically. For a classification tree, the Entropy or Gini index is used to create a decision tree for classification, while measures of mean-squared error (MSE) are used as the indices to build a regression tree, as shown in Eq. (4-24).

$$MSE(t) = \frac{\sum_{x_i \in t} \left(y_i - \bar{y}(t)\right)^2}{N} \tag{4-24}$$

where $MSE(t)$ is mean-squared error at node *t*; y_i is a response value in node *t*; x_i is a predictor value in node *t*; $\bar{y}(t)$ is average response value in node *t*; and *N* is the total number of branches in node *t*.

To build a regression tree, attributes and attribute splits are optimized using Eq. (4-25).

$$\Delta MSE(s^*, t) = \max_{s \in S} \Delta MES\ (s, t) = \max_{s \in S}(MSE(t) - MSE(t_L) - \ MSE(t_R) \tag{4-25}$$

where ΔMSE(s*,t) is optimal attribute and attribute split; ΔMES (s,t) is mean-squared error reduction for attribute t and split s, and s∊S; S is split assembly;

MSE(t_L) is the mean-squared error of the left branch of split s; and MSE(t_R) is the mean-squared error of the right branch of split s.

Based on the regression tree split, the factor importance of the mixed numerical and categorical factors can be computed by summing changes in the MSE due to splits on every attribute (factor) and dividing the sum by the number of branch nodes (MathWorks 2014). With the application of the Predictor Importance function in MATLAB, the factor importance of main wall, roof, exposed floor, basement wall, basement floor, space heating, hot water heating, and HRV with regard to energy consumption is illustrated in Fig. 4-29, which displays the sequence of the factor importance for the simulated factors. It can also be observed that the most influential factor is space heating and the second-most is the main wall among the simulated eight factors. Fig. 4-30 demonstrates the factor importance for the building envelope components, from which it can be concluded that main wall is the most important factor and basement wall is the second-most important among the building envelope elements. The factor importance ranking highlights the impacts of different design options on energy consumption, reflecting the factor sensitivity with regard to energy consumption for NZEH design.

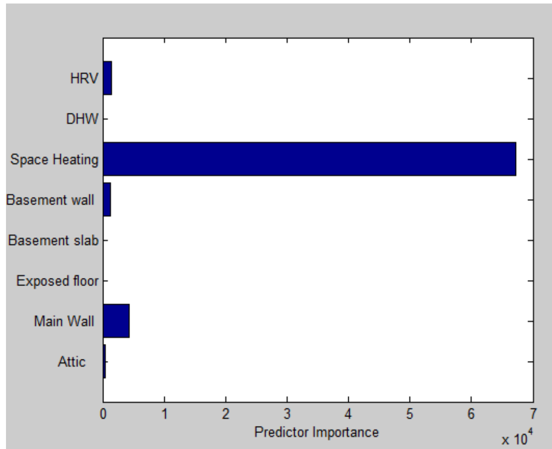


Fig. 4-29. Factor Ranking: All Factors

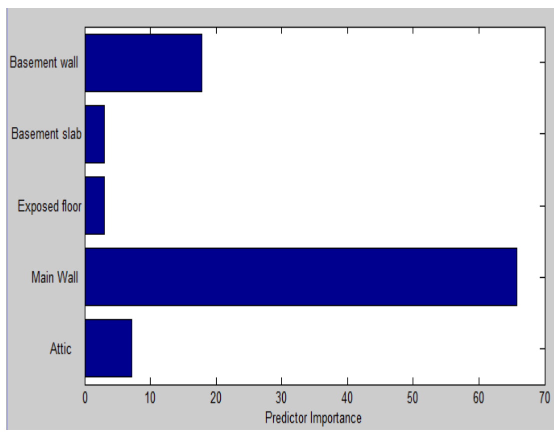


Fig. 4-30. Factor Ranking: Building Envelope

4.5 Temperature Set-point Simulation and Analysis

To evaluate the impact of heating temperature set-point on space heating of NZEHs, the Batch Version is utilized to simulate different heating temperature set-points with the initial design of the NZEH case. The heating temperature set-point is simulated from 15.0 °C to 24.0 °C, with the simulated energy usage for space heating displayed in Table 4-17. The fitted curve and function are demonstrated in Fig. 4-31, from which it can be observed that the energy usage for space heating is well fitted using the linear function expressed as Eq. (4-26), with the coefficient of determination (R^2) of 0.995.

Table 4-17 Temperature Set-point and Space Heating

Heating Temperature Set-point (°C)	Energy Usage for Space Heating (MJ)
15	14,321
16	16,012
17	17,286
18	18,294
19	20,416
20	21,594
21	23,039
22	24,978
23	26,764
24	28,740

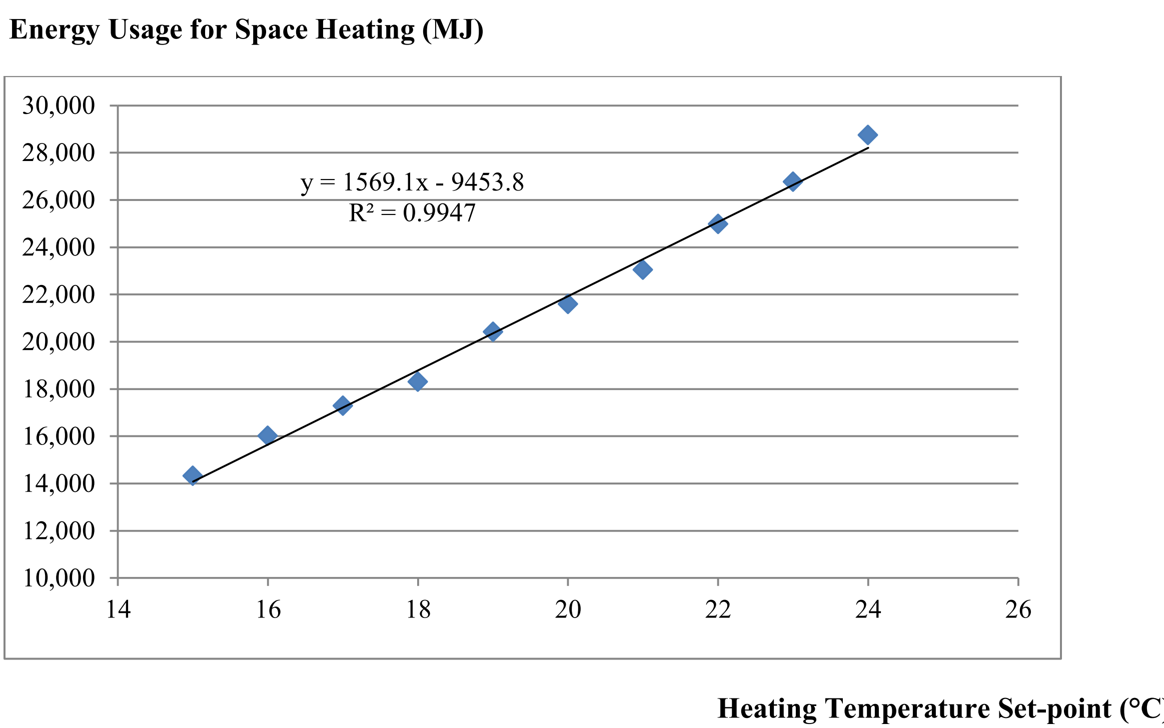


Fig. 4-31.Space Heating with Temperature Set-point

$$y = 1569.1\,x - 9453.8 \tag{4-26}$$

where y is the energy usage for space heating, and x is the heating temperature set-point.

The default heating temperature in HOT2000 is 21 °C. If the heating temperature is set to 24 °C, the energy usage for space heating will increase by 24.75%, while, if the heating temperature is set to 15 °C, the energy usage for space heating will be reduced by 37.84%. As these findings suggest, the temperature heating set-point has a considerable impact on energy usage for space heating.

4.6 Energy Generation Simulation and Analysis

For this NZEH case in Edmonton, 42 units of 308W monocrystalline silicon (mono-Si) PV panel are mounted on the south-facing roof with Slope 33° and Azimuth 0°, and connected with the grid. The energy generation system contributes the power of total 12.936W that is used to offset the energy consumption of the NZEH. The energy generation of the PV system mainly depends on the weather conditions, with solar radiation as the determining factor. RetScreen is utilized as the tool to estimate the energy generation for this NZEH, with the applied methodology expressed as Eq. (4-27) to Eq. (4-29) (Duffie and Beckman 1991).

$$E_{grid} = E_A \, \eta_{inv} \tag{4-27}$$

$$= E_p(1 - \lambda_p)(1 - \lambda_c) \, \eta_{inv} \tag{4-28}$$

$$= S \, \eta_p \, \overline{H}_t(1 - \lambda_p)(1 - \lambda_c) \, \eta_{inv} \tag{4-29}$$

where E_{grid} is energy available to grid; E_A is array energy available to load; E_p is energy delivered by PV array; η_{inv} is inverter efficiency; λ_p is miscellaneous PV array losses; λ_c is other power conditioning losses; S is array area; η_p is array efficiency, calculated using Eq. (4-30); $\overline{H}_t$ is average hourly irradiance in the plane of PV array.

$$\eta_p = \eta_r \left[1 - \beta_p (T_c - T_r)\right] \tag{4-30}$$

where η_r is PV efficiency at reference temperature T_r (= 25 °C); β_p is temperature coefficient for module efficiency; T_c is related temperature to mean monthly ambient temperature T_a by Eq. (4-31).

$$T_c - T_a = (219 + 832\,\overline{K_t})\,\frac{NOCT-20}{800} \tag{4-31}$$

where $NOCT$ is nominal operating cell temperature, and $\overline{K_t}$ is clearness index, calculated using Eq. (4-32).

$$\overline{K_t} = \frac{\overline{H}}{\overline{H}_0} \tag{4-32}$$

where $\overline{H}$ is monthly average daily solar radiation on a horizontal surface, which is calculated based on H_t (solar radiation at time *t*), and $\overline{H}_0$ is monthly average extraterrestrial daily solar radiation on a horizontal surface.

$$H_t = H_b R_b + H_d \left(\frac{1+\cos(\beta)}{2}\right) + H\rho \left(\frac{1-\cos(\beta)}{2}\right) \tag{4-33}$$

where $H\rho$ is diffuse reflectance of ground; β is the slope of PV array; R_b is the ratio of beam radiation on PV array to that on horizontal; H_b is beam global horizontal irradiance; and H_d is diffuse global horizontal irradiance.

With the solar radiation profile (Table 4-18) and the product specification and the parameters (Table 4-19) utilized, this solar PV system is estimated to yield an annual energy of 17.466 MWh; the estimated energy generation for each month is displayed as Table 4-20.

Table 4-18 Solar Radiation of Edmonton

Month	Daily solar radiation – horizontal (kWh/m²/d)	Daily solar radiation – tilted (kWh/m²/d)
January	1.03	2.60
February	2.05	4.00
March	3.63	5.39
April	4.80	5.61
May	5.92	6.11
June	5.96	5.85
July	6.11	6.13
August	4.75	5.19
September	3.46	4.42
October	2.18	3.61
November	1.29	3.00
December	0.77	2.14
Annual	**3.50**	**4.50**

Table 4-19 Energy Generation Model Parameters

Components	**Parameter**	Note
Photovoltaic		
Type	mono-Si	
Power capacity (kW)	12.81	
Manufacturer	Sunpower	
Model	mono-Si - SPR-305-WHT	42 unit(s)
Efficiency (%)	18.7%	
Nominal operating cell temperature (°C)	45	
Temperature coefficient (% / °C)	0.40%	
Solar collector area (m²)	69	
Miscellaneous losses (%)	14.0%	
Inverter		
Efficiency (%)	97.0%	
Capacity (kW)	7.0	
Miscellaneous losses (%)		

Table 4-20 Estimated Energy Generation

Month	Electricity Generated (MWh)
January	0.926
February	1.262
March	1.826
April	1.785
May	1.959
June	1.794
July	1.917
August	1.640
September	1.384
October	1.204
November	1.007
December	0.762
Annual	**17.466**

4.7 Summary

Design options for building envelope and mechanical devices are considered as means to conserve energy in an effort to achieve net-zero energy, and usually are proposed as technical suites. However, to achieve improved design for NZEHs, sophisticated information and knowledge are necessary in order to support informed design decisions. In this chapter, energy simulation is utilized as an approach to analyze the energy performance of design options of the main wall, exposed floor, attic, basement wall, basement floor, space heating, hot water heating, and HRV for NZEHs. The batch version of HOT2000 is employed to achieve automated energy simulation, and 16,200 design scenarios are analyzed for a NZEH design considering practical design options for building envelope and mechanical devices. Based on the simulation results, the energy consumption is modelled with the design options of building envelope and mechanical devices using linear regression and neural network approaches. The regression models provide a higher level of knowledge than do the technical suites that have been previously recommended for NZEH design, and they are less complicated than existing energy simulation methodologies in describing the energy consumption of different design scenarios. In order to identify influential factors for NZEH design, the impacts of such design variables as main wall, exposed floor, attic, basement wall, basement floor, space heating furnace, hot water tank, and ventilator are assessed and ranked. It is identified that space heating furnace is the dominant factor among the eight simulated variables and clusters of energy profiles, and main wall is the most influential factor for building envelope. Considering the impacts of temperature set-point on the energy usage for space heating, the energy usage for space heating is simulated and analyzed with regard to different temperature set-points as well. The energy generation prediction is analyzed based on the energy generation mechanism, weather profiles, and solar PV system parameters.

5 Energy Monitoring and Analysis of NZEHs

NZEHs are designed to achieve net-zero energy balance; however, the actual energy performance of NZEHs may differ from the design, a result which is caused by such factors as occupant behaviour and the level of precision of the construction process (e.g., varying levels of air-tightness). Thus, the actual performance of NZEHs must be monitored, which is also indicated by the responses from the surveyed NZEH occupants. The research objectives of this chapter thus include: (1) investigating the actual energy performance of NZEHs in detail; (2) proposing operation suggestions for NZEHs, (where the real-time energy monitoring provides feedback to owners, which is utilized in order to adjust and improve NZEH operation); and (3) modelling the energy consumption based on the monitoring data and analysis.

5.1 Energy Monitoring and Analysis Methodology

In this research, a sensor based monitoring system is utilized to collect detailed energy consumption data, and the energy generation data is derived from SolarLog, an off-the-shelf product from SMA America. The research methodology of this chapter is illustrated in Fig. 5-1. The inputs of the methodology include: (1) monitoring system design by means of sensor technology, (2) raw data from monitored energy consumption and generation, and (3) monitored indoor and outdoor temperature. With the collected data, the overall actual energy performance of NZEHs, including energy consumption, generation, and balance, is analyzed. Based on the energy performance analysis, the actual energy consumption is modelled using different methods that incorporate the occupant behaviour. Occupant behaviour, capacity of solar energy system, and building design comprise the constraints of this research. The actual energy performance, proposed operation recommendations, and energy consumption prediction models are the outputs of this chapter.

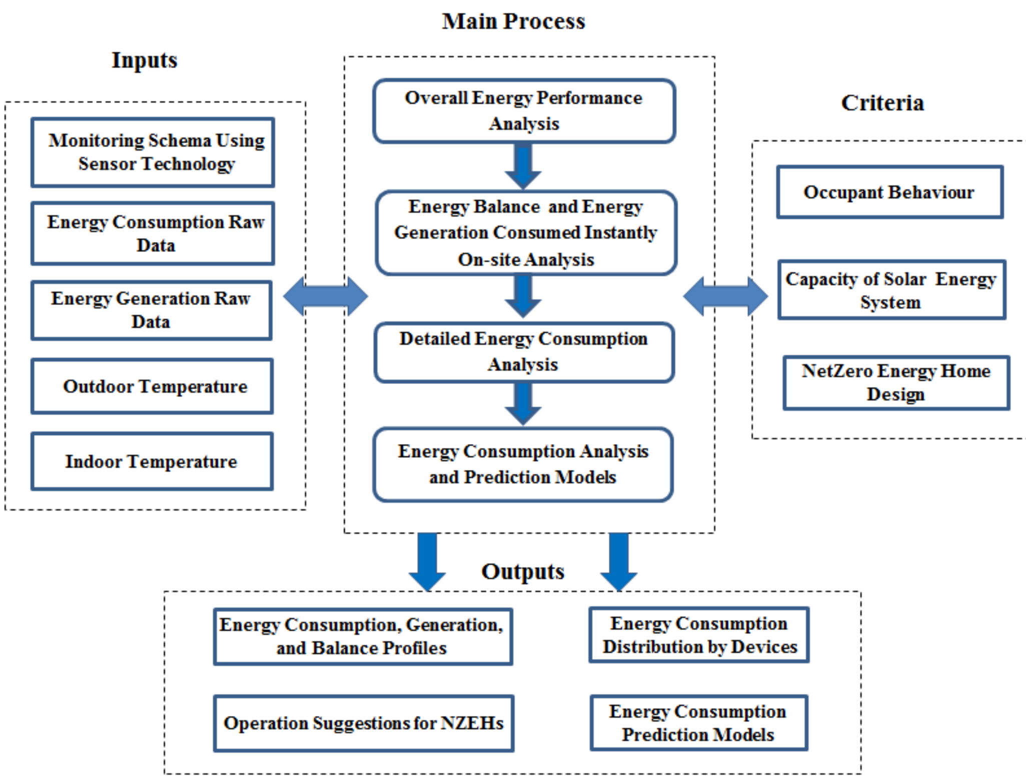


Fig. 5-1. Research Methodology

5.2 Sensor Instrument and Raw Data

5.2.1 Sensor Instrument

Electricity is the primary energy type used in the monitored NZEHs, thus current transformer (CT) sensors are installed in the electrical panel of the house in order to measure the electrical consumption details of major equipment and appliances; temperature sensors are used to monitor the indoor and outdoor temperature in this research. The collected data is processed and locally stored on a single-board computer, and is then transmitted to a database server at the University of Alberta via a secured Internet connection. The sensor instrument summary is presented in Table 5-1; the schematic diagrams of the sensor instrument and data transmission are illustrated in Fig. 5-2 and Fig. 5-3, and the actual installation is displayed in Fig. 5-4 and Fig. 5-5.

Table 5-1 Sensor Instrument Summary

System Function	Instrument Brand/Model	Note
Electricity Consumption Monitoring	Brultech/ Micro-100 Current Transformer	Two main phases of electrical panel
	Brultech/ Micro-40 Current Transformer	Other phases of electrical panel
	Brultech /GEM Energy Monitor	Processor
Indoor and Outdoor Temperature Monitoring	DHT11 Temperature Sensor	
	Arduino Mini/ATmega328 Microcontroller	Processor
Data Collection and Storage	Intel/ EPIC CPC800 Single-Board Computer	

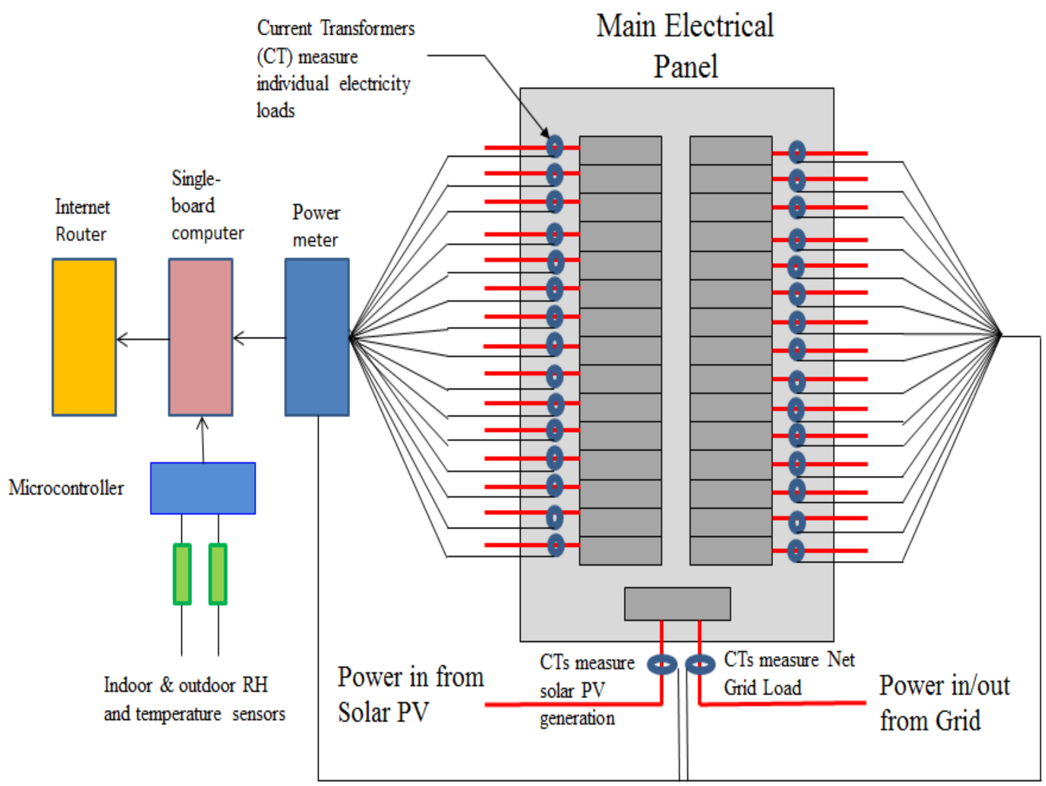


Fig. 5-2. Schematic Diagram of Sensor Instrument

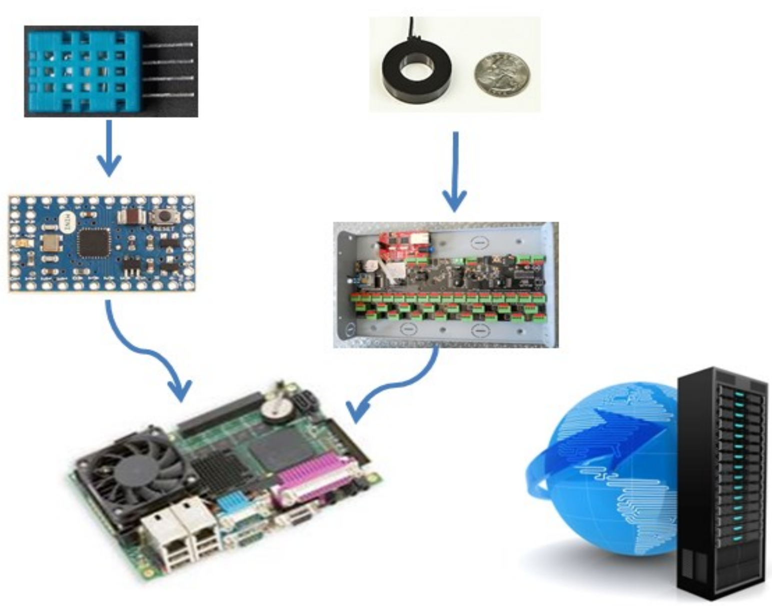


Fig. 5-3. Data Collection and Transmission

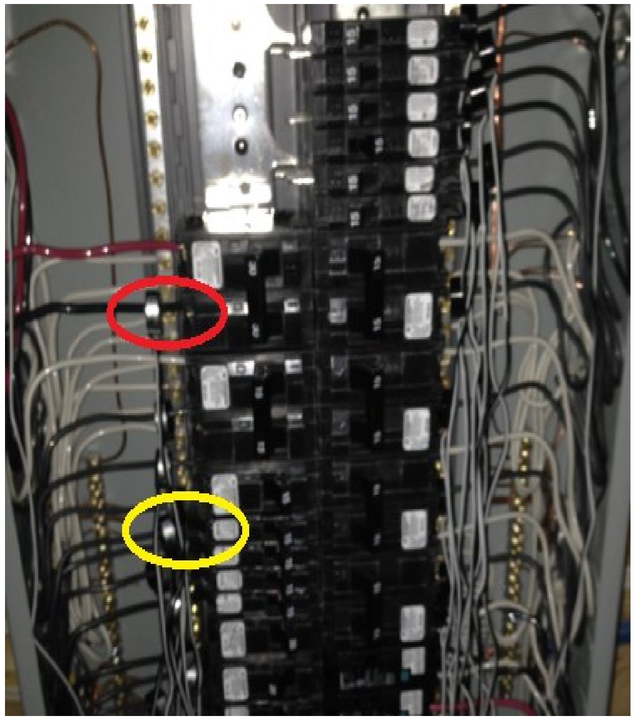


Fig. 5-4. Monitoring System Installation I

Fig. 5-5. Monitoring System Installation II

The energy used by various equipment and appliances, including space heating and cooling furnace, hot water tank, heat recovery ventilator (HRV), washer, dryer, fridge, range, and dishwasher is monitored using Brultech micro-40 CT sensors; these sensors are installed on the electricity panel, which is linked to the electrical wiring of the equipment and appliances, in order to measure the electricity used by the major equipment and appliances of NZEHs. Micro-100 CT sensors are linked with two main phases of the electricity panel, monitoring the electricity balance of NZEHs. Indoor and outdoor temperature is monitored with DHT11 temperature sensors and an Arduino Mini processor. The sensor instrument design details for the NZEH case, which is introduced in Chapter 4, are displayed in Table 5-2.

Table 5-2 Sensor Measurement Details

Measurement Target	Sensor Channel	Measurement Detail	Note
Electricity Consumption	Channel 1	Main A	Energy Balance
	Channel 2	Main B	Energy Balance
	Channel 3	Zuba A	Space Heating and cooling
	Channel 4	Range B	
	Channel 5	Fridge A	
	Channel 6	Exterior Plug B	
	Channel 7	Condenser A	Space Heating and cooling
	Channel 8	Range A	
	Channel 9	Hot Water Tank A	
	Channel 10	Zuba B	Space Heating and cooling
	Channel 11	Dryer A	
	Channel 12	Dryer B	
	Channel 13	Hot Water Tank B	
	Channel 14	Zuba B	Space Heating and cooling
	Channel 15	Washer B	
	Channel 16	Garburator	
	Channel 17	Dishwasher A	
	Channel 18	Zuba A	Space Heating and cooling
	Channel 19	Island Fridge A	
	Channel 20	HRV	
	Channel 21	Condenser B	Space Heating and cooling
Temperature	Channel 22	Outdoor temperature	
	Channel 23	Indoor temperature	

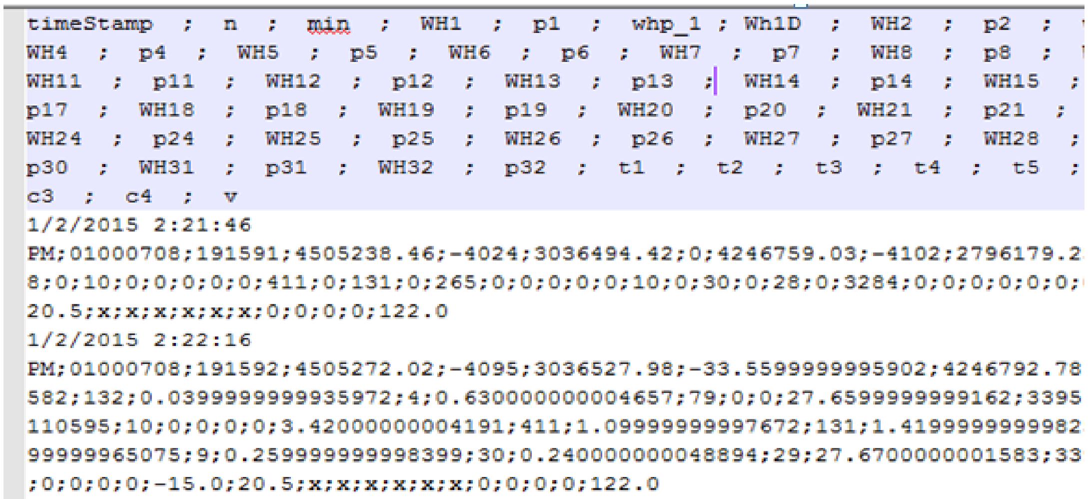
Due to the interaction between energy consumption and generation of NZEHs, the amount of measured energy of main A and main B on the electricity panel is the energy balance, which is the difference between the energy consumption and the energy generation at a given time. The energy balance is directional data, with positive and negative signs; the positive value indicates that extra electricity is injected into the electricity grid, and the negative value indicates that more electricity must be pulled from the grid. Only the electricity consumption of major equipment and appliances is measured using CTs in the monitoring system, so the total electricity consumption must be calculated using Eq. (5-1).

$$E^C = E^G - E^B \tag{5-1}$$

where E^C is the total energy consumption (kWh); E^G is the energy generation from solar PV (kWh); E^B is the energy balance (kWh), with positive or negative signs.

5.2.2 Raw Data from Sensors

The raw data of energy consumption collected from the CT sensors is in text format, and is collected at 30-second time intervals, as expressed in Fig. 5-6. The raw data is cleaned by removing outliers and noisy data, and the data collected through sensor-based monitoring is validated using the data from SolarLog. After the data cleaning and validation are complete, the raw data is plotted to illustrate the energy consumption pattern for appliances; an example of space heating is demonstrated in Fig. 5-7. The time interval of the raw data is accumulated at different intervals for different analyses: (1) the 30-second raw data is accumulated into 5-minute intervals, which is the time interval of SolarLog raw data, in order to analyze the energy balance and the energy consumed on-site; and (2) the raw data is accumulated into daily data for energy profile analysis, as shown in the following sections.



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WH4  ;  p4  ;  WH5  ;  p5  ;  WH6  ;  p6  ;  WH7  ;  p7  ;  WH8  ;  p8  ;
WH11  ;  p11  ;  WH12  ;  p12  ;  WH13  ;  p13  ;  WH14  ;  p14  ;  WH15  ;
p17  ;  WH18  ;  p18  ;  WH19  ;  p19  ;  WH20  ;  p20  ;  WH21  ;  p21  ;
WH24  ;  p24  ;  WH25  ;  p25  ;  WH26  ;  p26  ;  WH27  ;  p27  ;  WH28  ;
p30  ;  WH31  ;  p31  ;  WH32  ;  p32  ;  t1  ;  t2  ;  t3  ;  t4  ;  t5  ;
c3  ;  c4  ;  v
1/2/2015 2:21:46
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8;0;10;0;0;0;0;0;411;0;131;0;265;0;0;0;0;0;10;0;30;0;28;0;3284;0;0;0;0;0;0;
20.5;x;x;x;x;x;x;0;0;0;0;122.0
1/2/2015 2:22:16
PM;01000708;191592;4505272.02;-4095;3036527.98;-33.5599999995902;4246792.78
582;132;0.0399999999935972;4;0.630000000004657;79;0;0;27.6599999999162;3395
110595;10;0;0;0;0;3.42000000004191;411;1.09999999997672;131;1.4199999999982
99999965075;9;0.259999999998399;30;0.240000000048894;29;27.6700000001583;33
;0;0;0;0;-15.0;20.5;x;x;x;x;x;x;0;0;0;0;122.0
```

Fig. 5-6. Raw Data in Text Format

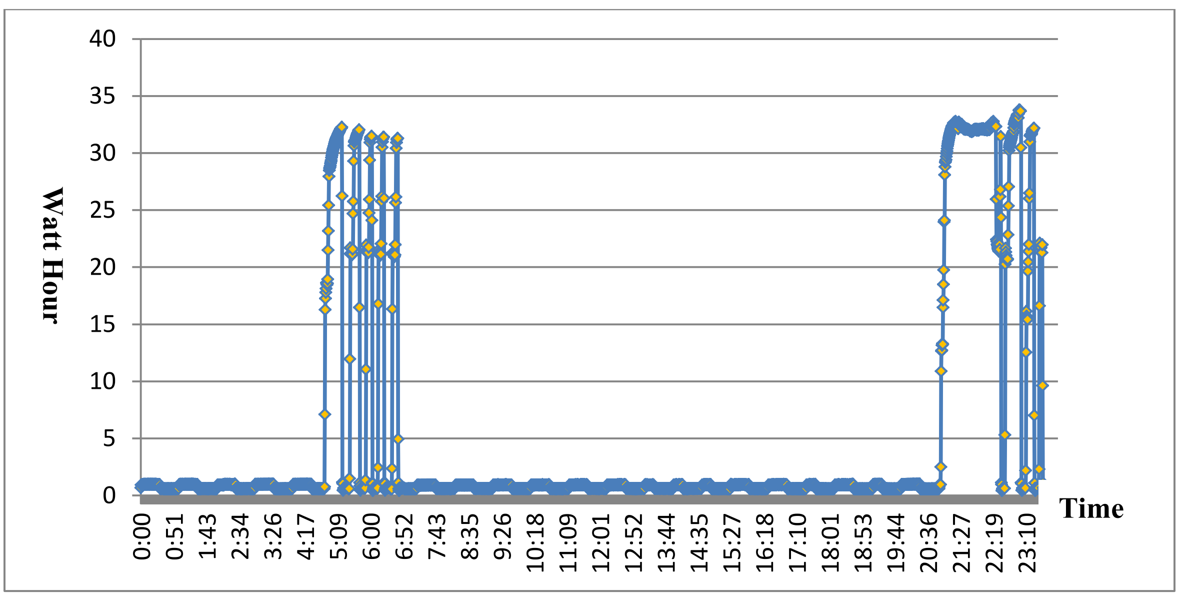

Fig. 5-7. Space Heating and Cooling Raw Data Profile: Sep. 3, 2014

5.3 Energy Performance Overall Analysis

The NZEH case described in Chapter 4 has been monitored since September, 2014; the annual energy performance between September, 2014, and August, 2015, is analyzed in this section. Considering that the actual energy performance is highly related to the weather conditions, the weather profile during the studied annual period is analyzed primarily, as follows.

5.3.1 Weather Profile of the Studied Period

The weather profile during the studied period is displayed in Table 5-3: (1) the minimum temperature during this period in Edmonton is –30.4 °C; (2) the maximum temperature of this period is 34.1 °C; (3) the total heating degree days (HDDs), which is the sum of the number of degrees Celsius that the mean temperature is below 18 °C for the given days (Environment Canada 2015), is 4,712; and (4) the total cooling degree days (CDDs), which is the sum of the number of degrees Celsius that the mean temperature is above 18 °C for the given days (Environment Canada 2015), is 152. The HDDs and CDDs are the determining factors of energy usage for space heating and cooling.

Table 5-3 Edmonton Climate Profile (September, 2014, to August, 2015)*

Month	Heating Degree Days (HDDs)	Cooling Degree Days (CDDs)	Temperature		
			Maximum	Mean	Minimum
Sep-2014	176.2	2.5	29.0 °C	12.2 °C	–2.0 °C
Oct-2014	316.5	0.0	22.3 °C	7.8 °C	–5.3 °C
Nov-2014	745.0	0.0	9.3 °C	–6.8 °C	–29.9 °C
Dec-2014	765.4	0.0	12.7 °C	–6.7 °C	–21.9 °C
Jan-2015	795.8	0.0	9.9 °C	–7.7 °C	–30.4 °C
Feb-2015	754.1	0.0	8.3 °C	–8.9 °C	–22.3 °C
Mar-2015	524.8	0.0	18.3 °C	1.1 °C	–18.8 °C
Apr-2015	326.1	0.0	25.2 °C	6.6 °C	–5.7 °C

May-2015	201.2	2.1	28.1 °C	11.6 °C	–2.3 °C
Jun-2015	50.1	37.0	32.2 °C	17.6 °C	5.0 °C
Jul-2015	16.1	64.6	34.1 °C	19.6 °C	8.9 °C
Aug-2015	40.2	46.2	31.0 °C	18.2 °C	5.9 °C

* http://edmonton.weatherstats.ca/metrics/hdd.html

5.3.2 Overall Energy Performance and Analysis

During the analyzed period, the monitored NZEH consumed 16,381.24 kWh of electricity, while the solar PV system generated 15,711.86 kWh of electricity, which results in an energy deficit of 669.38 kWh.

The monthly energy consumption, generation, and balance are displayed in Table 5-4; it can be observed that overall there are energy deficits during the winter season (Oct., 2014 to Feb., 2015), and there are energy surplus for other seasons.

Table 5-4 Monitored Energy Performance Profile

Month	Energy Consumption (kWh)	Energy Generation (kWh)	Energy Balance (kWh)
Sep-2014	968.05	1,386.47	418.42
Oct-2014	1,247.05	1,160.41	–86.64
Nov-2014	2,177.68	273.22	–1,904.46
Dec-2014	1,995.74	294.11	–1,701.63
Jan-2015	2,095.12	413.16	–1,681.96
Feb-2015	1,914.73	520.33	–1,394.40
Mar-2015	1,421.37	1,649.37	228.00
Apr-2015	1,128.65	1,795.31	666.66
May-2015	926.22	2,291.94	1,365.72
Jun-2015	747.93	1,981.05	1,233.12
Jul-2015	964.88	2,150.60	1,185.72
Aug-2015	793.84	1,795.90	1,002.06
Total	**16,381.24**	**15,711.86**	**–669.38**

The daily energy consumption, generation, and balance are plotted in Fig. 5-8, in which the outdoor temperature is also displayed. It can be observed that the energy consumption, energy generation, and energy balance are highly correlated with outdoor temperature, which proves to be a key indicator with regard to energy performance of NZEHs.

5.4 Energy Consumption Analysis

Energy consumption is a major issue for NZEHs, which is analyzed in great detail in this research. The raw data of energy consumption, which is used for space heating and cooling, DHW heating, HRV, and appliances, etc., comes from the monitoring system; other energy usage, such as lighting and plug outlets, is calculated using energy balance and energy generation. The monthly energy consumption distribution by devices is presented in Table 5-5; the overall (annual) energy consumption distribution is displayed in Fig. 5-9, in which "Other" energy consumption includes lighting, plug outlets, garburator, and garage energy usage. From Table 5-5 and Fig. 5-9, it can be observe that: (1) overall space heating and cooling consumes *more than 50%* of the total energy usage of the NZEH, although air source heat pump technology is utilized to improve the energy efficiency for space heating. (2) The highest energy usage for space heating occurs in November, 2014, and accounts for more than *eight times* the lowest energy usage in August, 2015; thus, space heating appears as a major issue for the winter season in cold regions. (3) DHW is the second-highest energy consumer despite the utilization of heat pump technology, and maintains a comparatively consistent level across different months. (4) Dryer consumes 3.5% of the annual

Table 5-5 Energy Consumption Distribution

Items	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Overall	
													kWh	%
Total Energy Consumption (kWh)	**968.1**	**1,247.1**	**2,177.7**	**1,995.7**	**2,095.1**	**1,914.7**	**1,421.4**	**1,128.7**	**926.2**	**747.9**	**964.9**	**793.8**	**16,381.3**	
Space Heating & Cooling	341.41	616.65	1,658.48	1,462.65	1,496.38	1,420.57	700.05	575.26	293.57	221.24	319.66	194.37	9,300.27	56.8%
DHW	168.97	183.12	154.96	173.29	202.96	169.53	205.75	172.97	223.60	148.31	177.68	138.43	2,119.56	12.9%
HRV	76.22	66.53	70.00	32.82	27.73	22.20	30.45	54.34	55.13	63.37	70.75	74.58	644.11	3.9%
Dryer	49.05	71.46	50.42	56.03	56.79	47.33	36.04	34.33	40.27	38.61	43.56	56.21	580.11	3.5%
Washer	6.77	10.85	7.07	7.61	8.36	5.87	12.07	10.74	9.37	6.65	12.21	8.27	105.84	0.6%
Range	55.89	66.78	45.55	48.44	59.19	48.77	74.74	56.90	50.59	36.04	59.81	43.82	646.51	3.9%
Fridge	40.75	38.80	35.20	37.29	38.15	35.58	46.71	36.50	48.07	43.49	61.97	71.51	534.04	3.3%
Island Fridge	0.18	0.59	1.35	14.36	41.03	27.97	34.33	44.68	49.54	46.50	48.74	48.55	357.82	2.2%
Dishwasher	13.74	14.60	12.98	11.27	10.67	9.66	5.62	7.54	9.48	8.83	11.44	10.38	126.22	0.8%
Exterior	55.62	17.80	0.51	0.36	0.36	0.32	0.24	0.21	0.26	0.19	0.22	0.21	76.30	0.5%
Others	159.44	159.88	141.16	151.63	153.50	126.91	275.37	135.19	146.33	134.70	158.85	147.52	1,890.47	11.5%

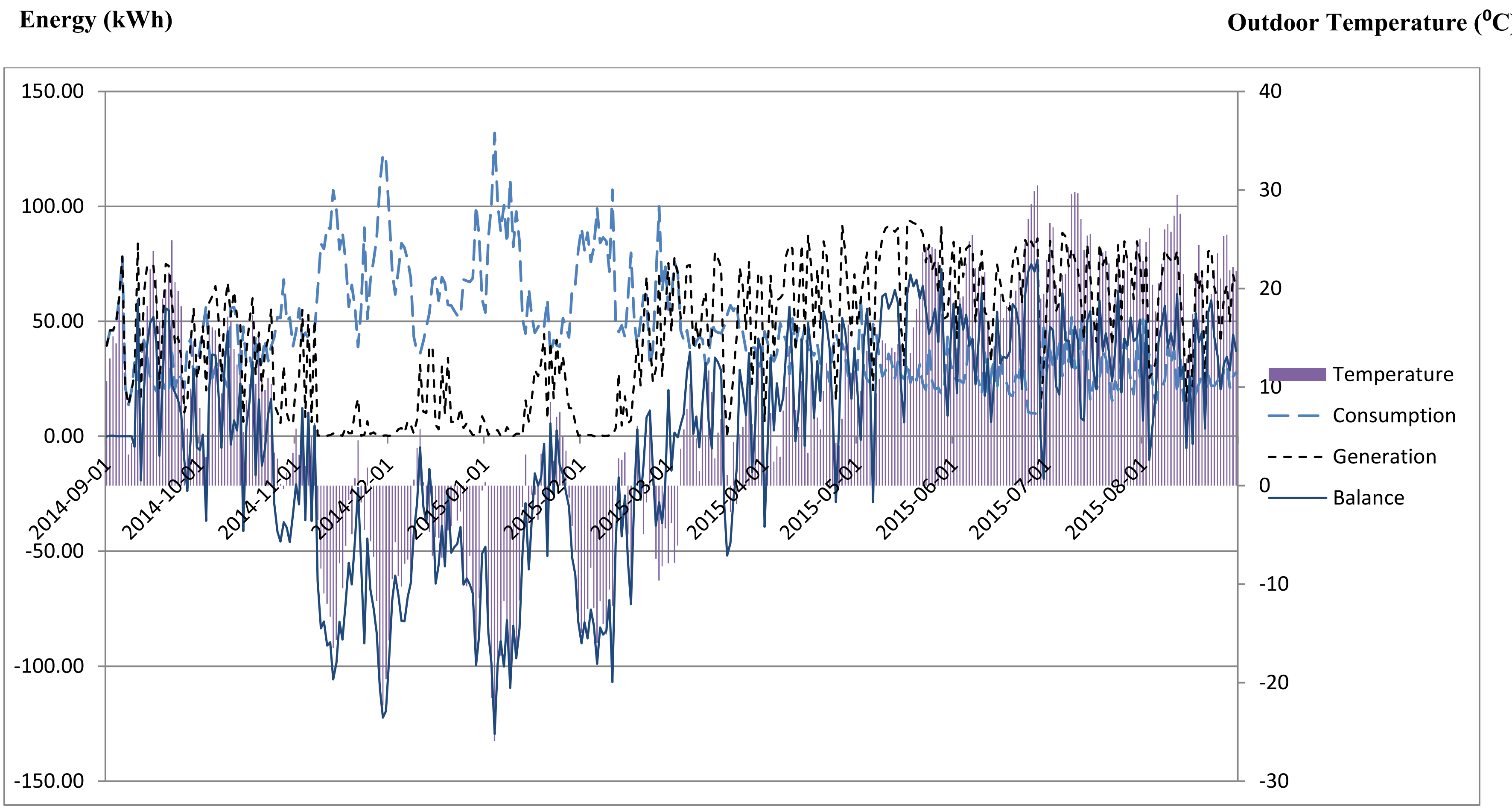

Fig. 5-8. Daily Energy Consumption, Generation, and Balance

energy usage, and accounts for *more than 500 times* the energy used by washer. (5) The exterior energy used is quite small, accounting for only 0.5% of annual energy consumption.

Both the daily energy consumption of primary devices and the outdoor temperature are illustrated in Fig. 5-10, from which it can be observed that the daily energy usage by space heating/cooling fluctuates and is correlated with outdoor temperature, while other consumption is barely correlated to outdoor temperature.

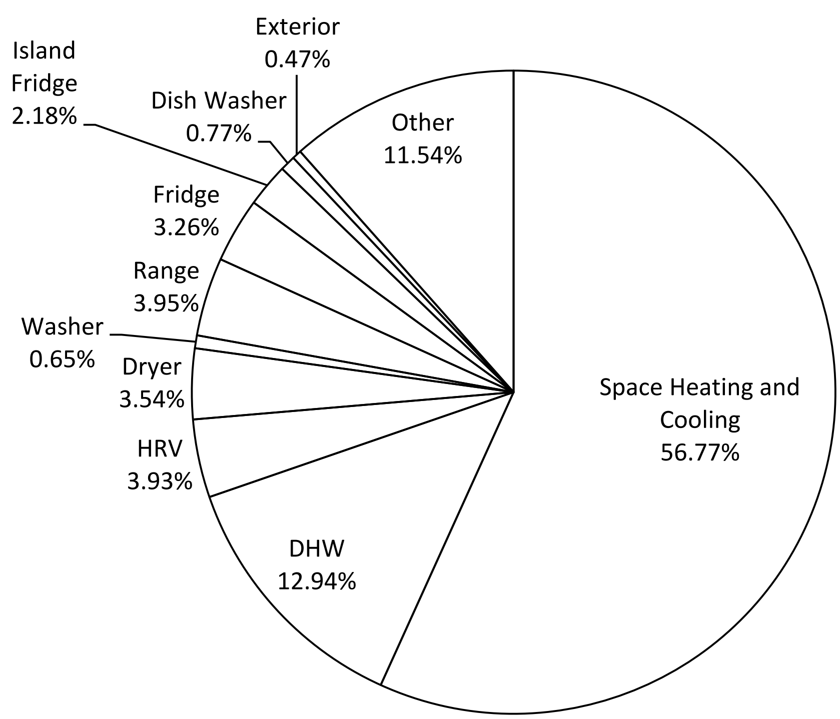

Fig. 5-9. Annual Energy Consumption Distribution

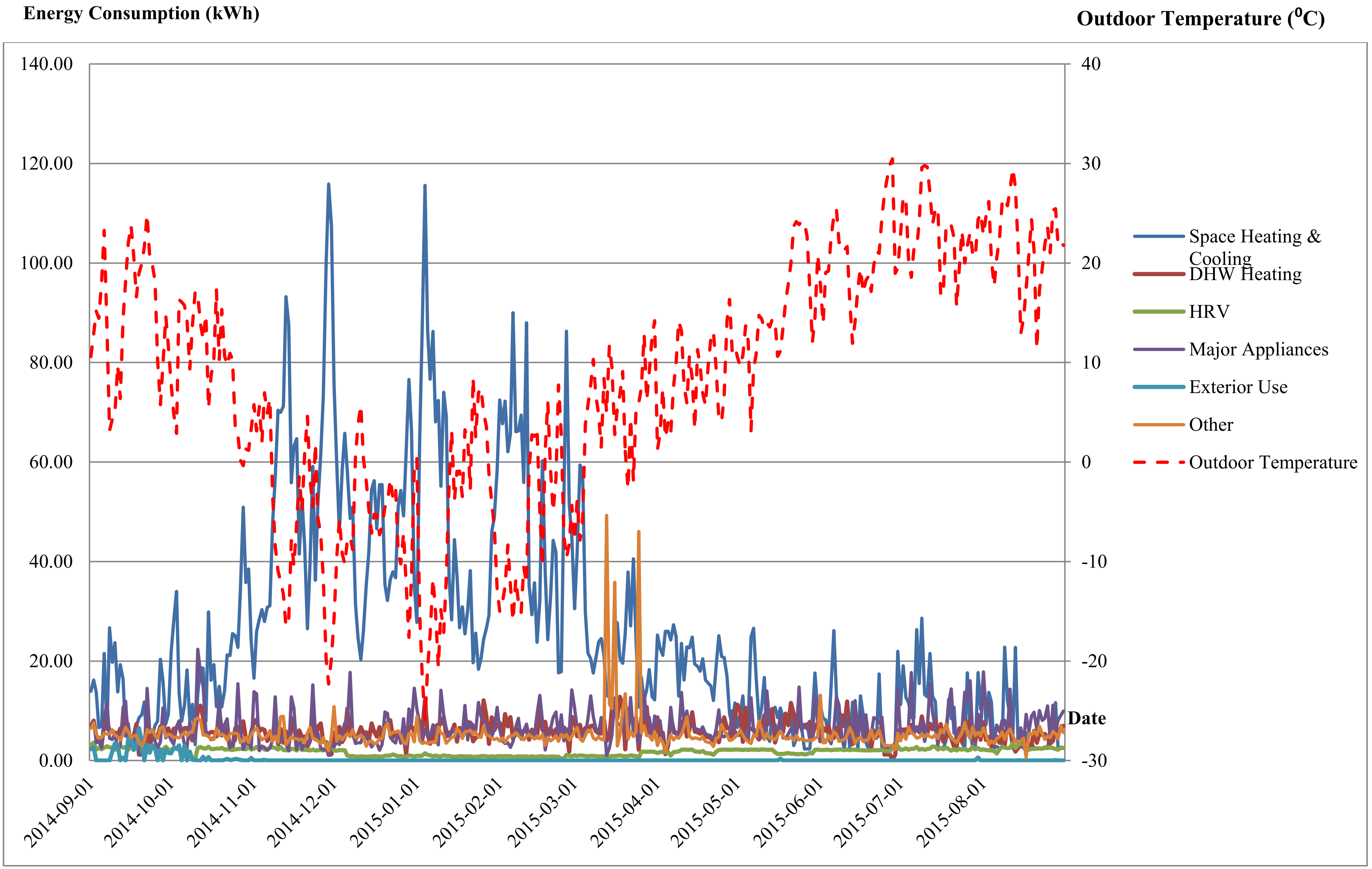

Fig. 5-10. Energy Consumption Daily Profile by Device versus Outdoor Temperature

Considering that occupant activity is a driving factor for energy usage, the total energy consumption is categorized into two types in this chapter; (1) *occupant-driven consumption*: this type of energy consumption is directly and entirely controlled by occupant activities at home by switching power on/off or plugging in/unplugging (e.g., range, dishwasher, plug, lighting, washer, and dryer); and (2) *less-occupant-driven consumption*: the energy consumption is less controlled by occupant activities, and usually the devices run continuously (e.g., space heating and cooling, HRV, and fridge). The two categories of energy consumption entail different determining factors, and are analyzed in the following sections.

5.4.1 Occupant-driven Consumption

(1) Analysis of Occupant-driven Consumption

This type of energy consumption is directly related to occupant activities, and in this research it is found that the consumption level on working days is different than that on non-working days. On working days, the energy use of these devices in general is consistent and averages 14.88 kWh/day, as shown in Fig. 5-11. On non-working days, which includes weekends and statutory holidays, the energy consumption measures a large amount of fluctuation from day to day with an average of 17.28 kWh, as shown in Fig. 5-12. On average, the daily consumption on non-working days is approximately 16.13% higher than on working days, which means more at-home activities occurred on non-working days.

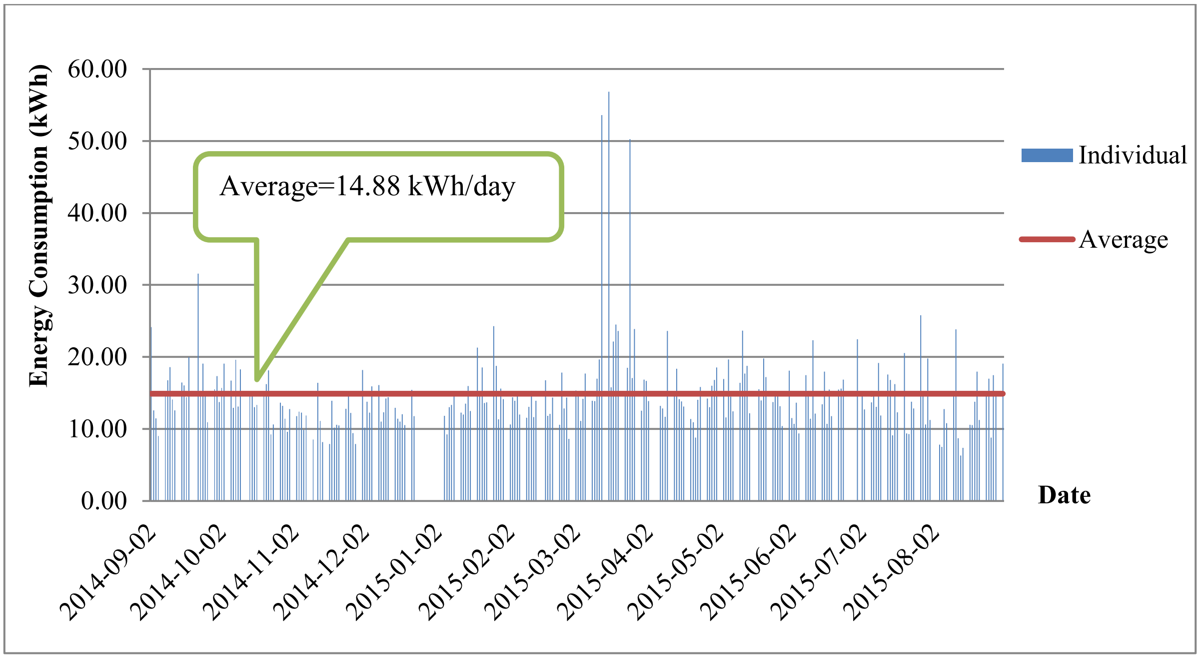

Fig. 5-11. Occupant-activity-related Energy Consumption on Working Days

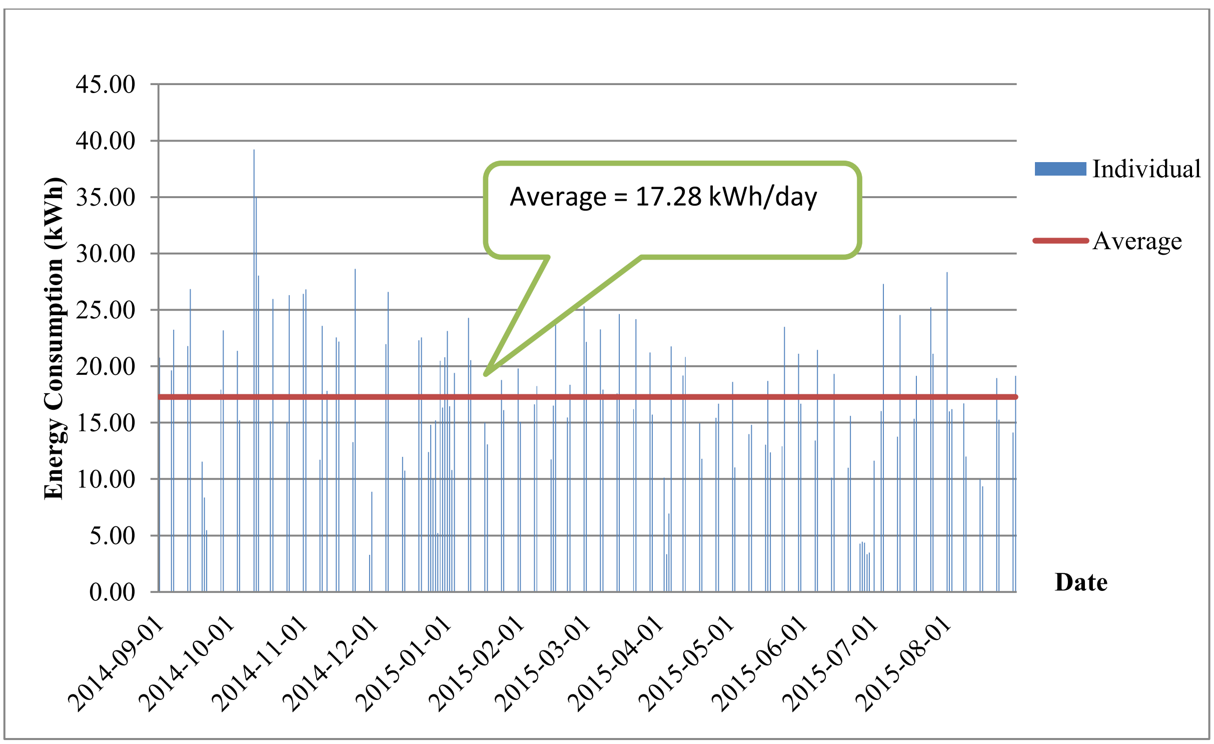

Fig. 5-12. Occupant-activity-related Energy Consumption on Non-working Days

(2) Analysis of Phantom Load

Phantom load is defined as the occupant-activity-related energy consumption on non-occupied days in this research, which is the stand-by energy load of plug-in devices. It can be observed from Fig. 5-11 that the energy consumption on non-working days fluctuates tremendously; this is due to the fact that the NZEH is either occupied or non-occupied entirely on non-working days. In this research, the energy consumption by *hot water tank* and *range* is used as the indicator of non-occupancy of NZEHs, and the phantom load is the occupant-activity-related energy usage on those non-occupied days. As shown in Fig. 5-13, there are four non-occupied segments during the monitored period; during the non-occupied days, the energy usage by the hot water tank is low (less than 2 kWh/day) and the energy consumed by the range is trivial (0.11 kWh/day). For this monitored NZEH, the lowest phantom load is 3.28 kWh/day, which occurs on November 29, 2014. On this day, hot water heating consumes 1.13 kWh when no hot water is used, accounting for 34.34% of the phantom load. A significant proportion of the "other" category of energy usage, referring to the phantom loads of plug-in devices, consumes 1.99 kWh, which is 60% of the phantom load on that day.

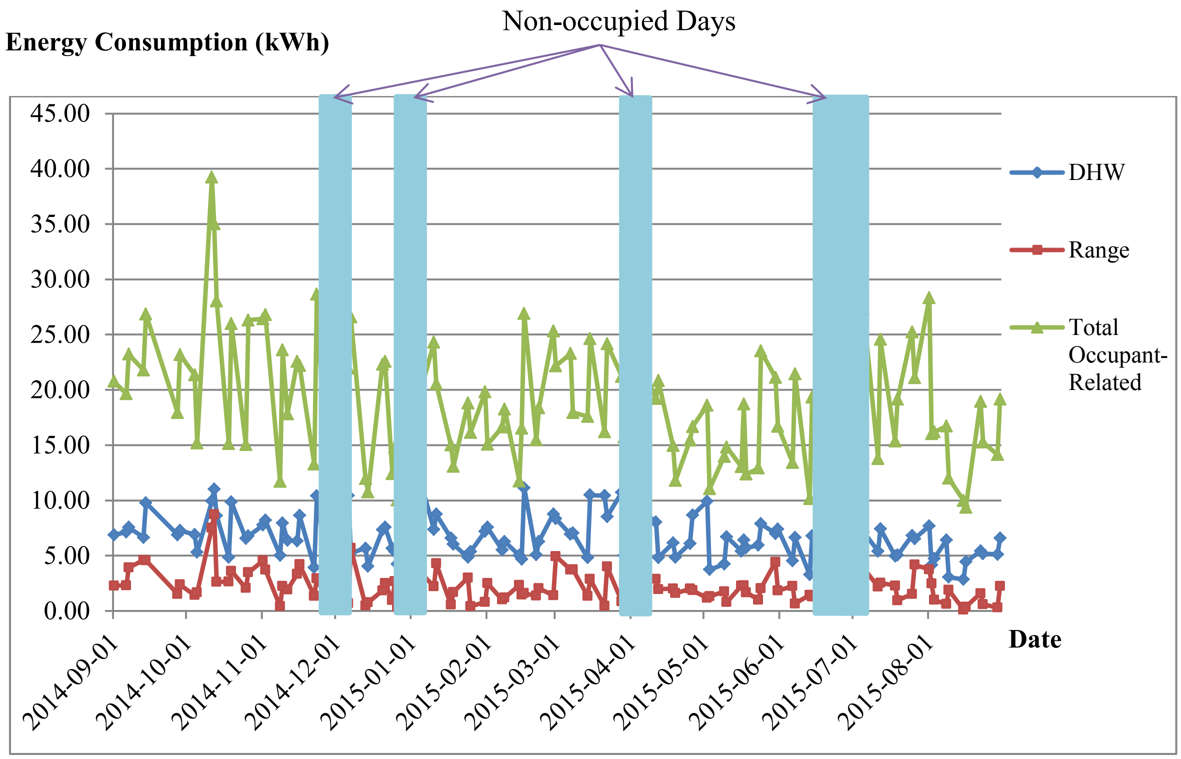

Fig. 5-13. Phantom Load Analysis

Table 5-6 Non-occupied Days and Phantom Loads

Date	DHW (kWh)	Range (kWh)	Occupant-driven Consumption (kWh)
2014-11-29	1.13	0.11	3.28
2014-11-30	1.26	0.11	8.89
2014-12-28	1.28	0.11	5.21
2015-04-04	1.27	0.11	3.34
2015-06-25	1.21	0.11	4.29
2015-06-26	1.25	0.11	4.44
2015-06-27	1.21	0.11	4.35
2015-06-28	0.13	0.11	3.35
2015-06-29	1.17	0.11	3.48

5.4.2 Less-occupant-driven Consumption

This type of energy consumption is less controlled by occupant activities, and usually the devices run continually during occupancy (e.g., space heating, HRV, and fridge). The detailed analysis for less-occupant-driven consumption is shown in the following sections.

a. Analysis of Energy Usage for Space Heating and Cooling

The energy usage for space heating and cooling in winter is a major issue for the NZEHs in cold regions, and as previously discussed, the energy consumption for space heating in November, 2014, accounts for eight times that of August, 2015. Usually, the indoor temperature is set near 21 °C throughout the entire year, and the dramatic change in space heating energy use is mainly caused by extremely low outdoor temperature. Furthermore, considering that the indoor and outdoor temperature difference governs the heat loss with regard to space heating, Eq. (5-2) is applied to fit the relationship between energy usage for space heating and cooling and the absolute value of indoor-outdoor temperature difference, with a coefficient of determination (R^2) of 0.8973. The fitted curve of daily energy usage by space heating and cooling and the absolute value of temperature difference is illustrated in Fig. 5-14. It can be observed that the energy usage for space heating and cooling is not proportional to the indoor-outdoor temperature difference, which is caused by the inconsistent coefficient of performance (COP) of the space heating and cooling furnace (Mitsubishi Electric 2015) and the HRV (Venmar 2012) under different outdoor temperatures.

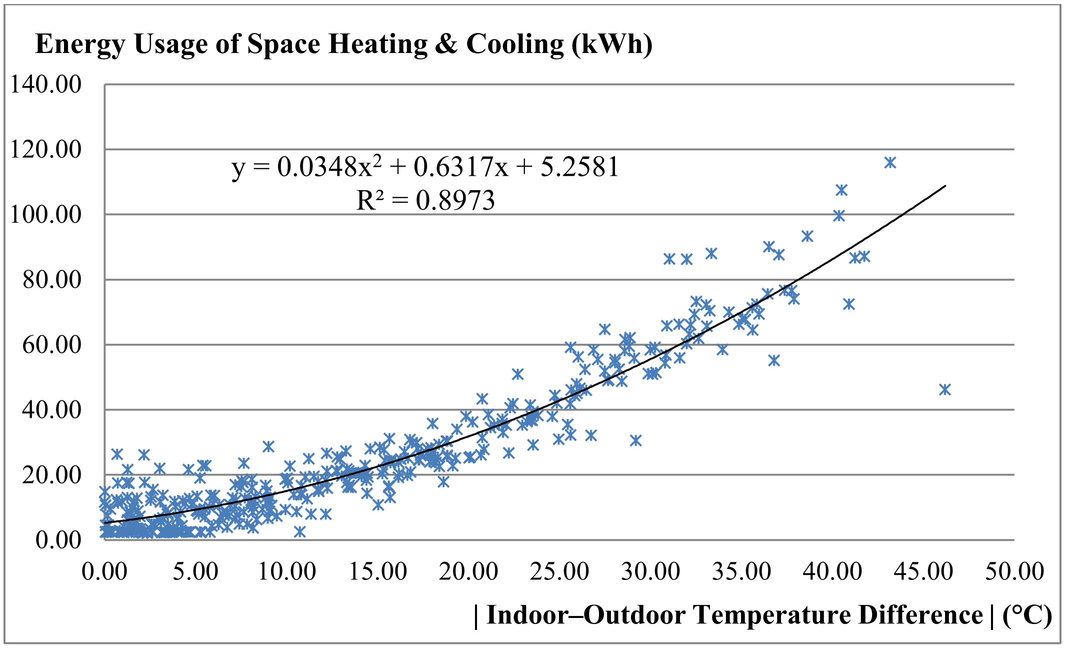

Fig. 5-14. Energy Usage of Spacing Heating/Cooling and Temperature Difference

$$y = 0.0348x^2 + 0.6317x + 5.2581 \qquad (5\text{-}2)$$

where y is the daily energy consumption for space heating and cooling (kWh); x is the indoor and outdoor temperature difference (°C).

b. Analysis of Energy Usage for HRV and Fridge

The energy consumed by the main fridge ranges consistently between 0.6 and 2.2 kWh/day, as shown in Fig. 5-15. The energy usage of HRV has dropped from approximately 2.5 kWh/day at the end of November, 2014, to 1.0 kWh/day, which was recovered at the end of March, 2015. From Fig. 5-14, it can be observed that, when the outdoor temperature drops, the HRV energy usage drops as well, which indicates that the low temperature may inhibit the operation of the HRV, which is also evidenced in the field study (dPoint Technologies 2015).

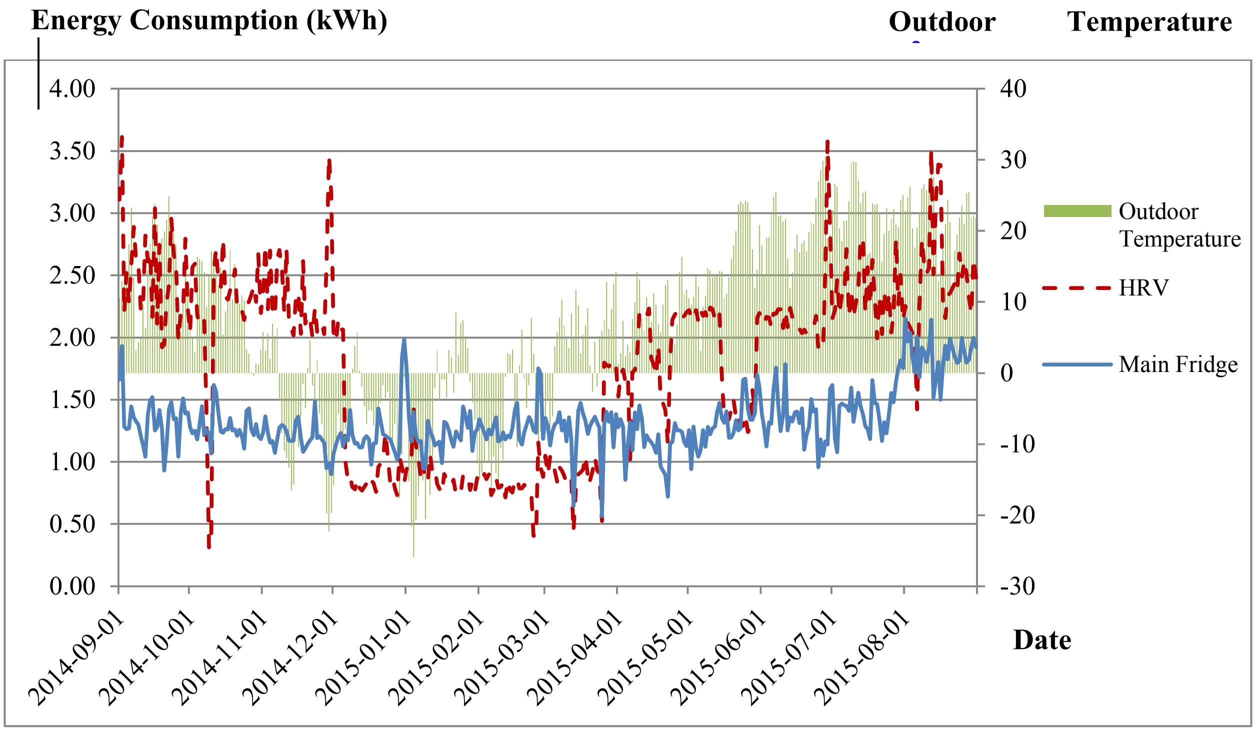

Fig. 5-15. Energy Consumption for HRV and Fridge

To describe energy consumption using mathematical models, two different mathematic approaches are proposed to model energy consumption for the NZEH in this research, which can also be used for the purpose of energy prediction. The coefficient of determination (R^2) is used to compare the goodness of the models. R^2 measures the goodness of fit, indicating how closely values obtained from fitting a model match the dependent variable; R^2 conveys the proportionate amount of variation in the response variable y, which is explained by the independent variable X in the model. The larger the R^2, the more variability is explained by the model. R^2 is calculated through Eq. (5-3) to Eq. (5-5) [23, 24].

$$SST = \sum(y_i - \bar{y})^2 \qquad (5\text{-}3)$$

$$SSE = \sum(y_i - \hat{y}_i)^2 \qquad (5\text{-}4)$$

$$R^2 = 1 - \frac{SSE}{SST} \tag{5-5}$$

where y_i is observed response value; $\bar{y}$ is average observed response value; $\hat{y}_i$ is fitted response value; SSE is the sum of squared error; SST is the sum of squared total, also known as regression identity.

5.4.3 Energy Consumption Polynomial Model

Based on the energy consumption analysis, an energy consumption Polynomial model for the NZEH is proposed with two categories: ***occupant-driven consumption*** and ***less-occupant-driven consumption***. (1) Occupant-driven consumption covers energy usage for such devices as washer, dryer, dishwasher, range, hot water tank, lighting, and electrical outlets. The predicted energy consumption depends on the categorical variables of working days and non-working days in the prediction model. (2) Less-occupant-driven consumption is the energy usage for space heating, HRV, and fridge. The variable used to predict energy consumption for space heating is the absolute value of indoor-outdoor temperature differences, and the energy consumption for HRV and fridge is an averaged constant value. The proposed prediction model is expressed as Eq. (5-6) to Eq. (5-9).

$$E_T^C = E_{OC}^D + E_{OC}^L \tag{5-6}$$

$$= E_{OC}^D + E^F + E^H + y \tag{5-7}$$

$$= E_{OC}^D + E^F + E^H + 0.0348x^2 + 0.6317x + 5.2581 \tag{5-8}$$

$$E_{OC}^D = \begin{cases} E_{OC}^W, & for\ working\ days \\ E_{OC}^N, & for\ non-working\ days \end{cases} \tag{5-9}$$

where E_T^C is the total predicted daily energy consumption (kWh); E_{OC}^D is the occupant-driven energy consumption (kWh); E_{OC}^L is the less-occupant-driven energy consumption (kWh); E^F is the daily average energy consumption by fridge (kWh); E^H is the daily average energy consumption by HRV (kWh); E_{OC}^W is the occupant-driven energy consumption on working days (kWh); E_{OC}^N is the occupant-driven energy consumption on non-working days (kWh); y is the daily energy consumption for space heating and cooling (kWh); x is the absolute value of indoor-outdoor temperature differences (°C).

With the proposed Polynomial prediction model, the total energy consumption is modelled with an R^2 of 0.86.

5.4.4 Energy Consumption Regression Model

Based on the energy consumption analysis, it is found that the energy consumption level is mainly determined by two exterior factors, which are indoor-outdoor temperature difference and working day/non-working day. Therefore, such regression methods as linear regression and decision tree are proposed in order to model the energy consumption of the NZEH, with the two exterior factors as predictor variables in this research.

(1) General Linear Regression

With the Least-Square fit method applied for the collected data, the general linear regression model in Wilkinson notation format is proposed for the NZEH; the absolute value of indoor-outdoor temperature difference consists the numerical variable, and working/non-working day is the categorical variable. The fitted linear regression is displayed as Eq. (5-10), and the estimated coefficients and statistical parameters are listed in Table 5-7. The model performance of estimated energy consumption versus actual energy consumption is illustrated in Fig. 5-16, with an R^2 value of 0.892, and the error over estimated energy consumption is presented in Fig. 5-17. From the linear regression results, it can be concluded that the energy consumption is mainly determined by the indoor-outdoor temperature and whether or not it is a non-working day.

$$y \sim 1 + x1 + x2 \tag{5-10}$$

where y is the estimated energy consumption (kWh); x_1 is the absolute value of indoor-outdoor temperature difference (°C); and x_2 is the categorical variable of working/non-working day, with 0 representing working day and 1 referring to non-working day.

Table 5-7 Estimated Coefficients and Statistical Parameters

	Estimate	Squared Error (SE)	*t*-stat	pVal
Intercept	19.16	0.98	19.62	5.46e-57
x_1	1.83	0.05	36.64	4.46e-117
x_{2_1}	2.01	1.18	1.70	0.09

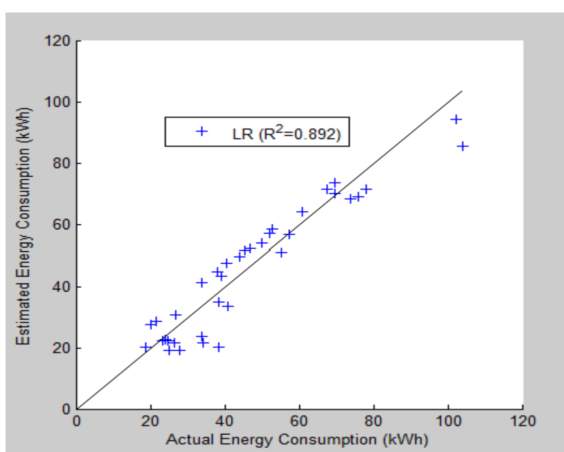

Fig. 5-16. Estimated versus Actual Energy Consumption (Linear Regression)

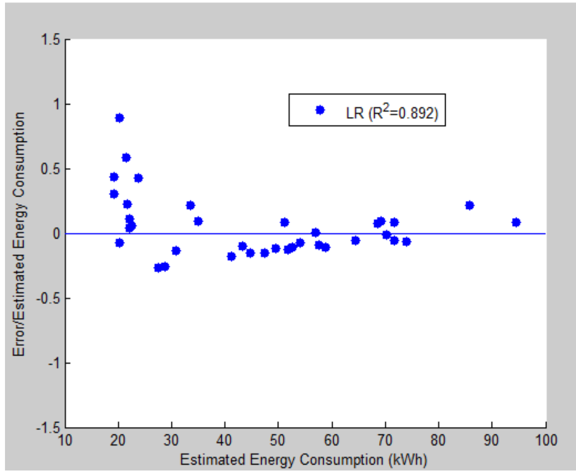

Fig. 5-17. Error/Estimated Energy Consumption (Linear Regression)

(2) Regression Decision Tree

With the measures of mean-squared error (MSE) used as the indices and attributes and attribute splits optimized to build a regression tree (see section 4.4.3 of Chapter 4), a regression decision tree is built as pictured in Fig. 5-18, with an R^2 of 0.872. From Fig. 5-18, it can be observed that the energy consumption is mainly determined by the temperature difference, when the temperature difference is high.

Among the three proposed energy consumption prediction models, the linear regression is proven to be a better prediction model in terms of R^2.

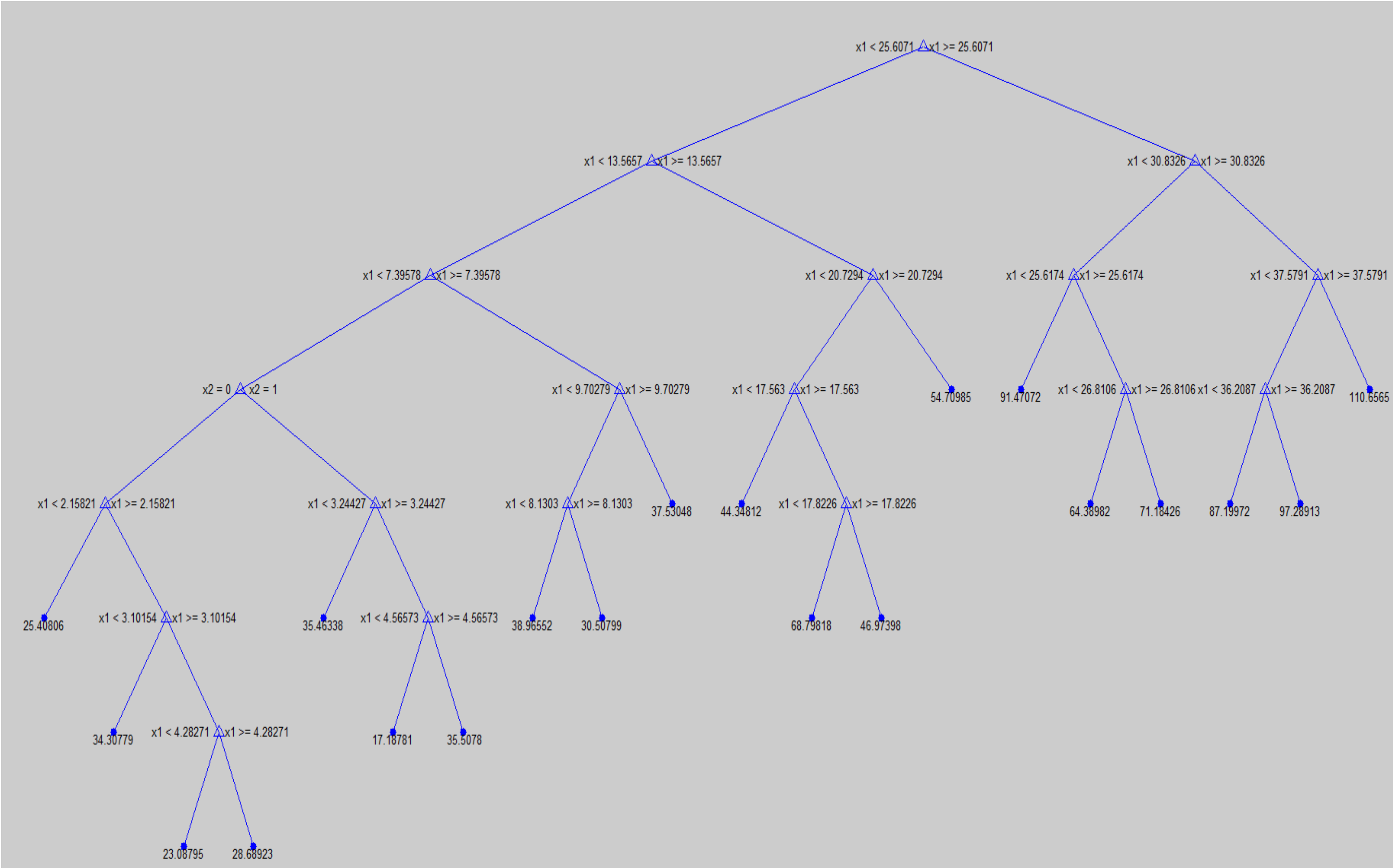

Fig. 5-18. Regression Decision Tree

5.5 Energy Generation and Balance Analysis

5.5.1 Energy Generation Analysis

A grid-connected solar PV system with two inverters is used as the means of energy generation for the monitored NZEH. The first inverter is connected to 28 solar PV panels of 308 W, and the second is connected to 14 solar PV panels of 308 W, which constitute the energy generation system of 12.94 kW. With the data from the SolarLog system, the actual monthly energy generation from the two inverters is displayed in Fig. 5-19, from which it can be observed that there is plenty of energy generated during the summer season, while little energy is generated during the winter season.

Energy Generation (kWh)

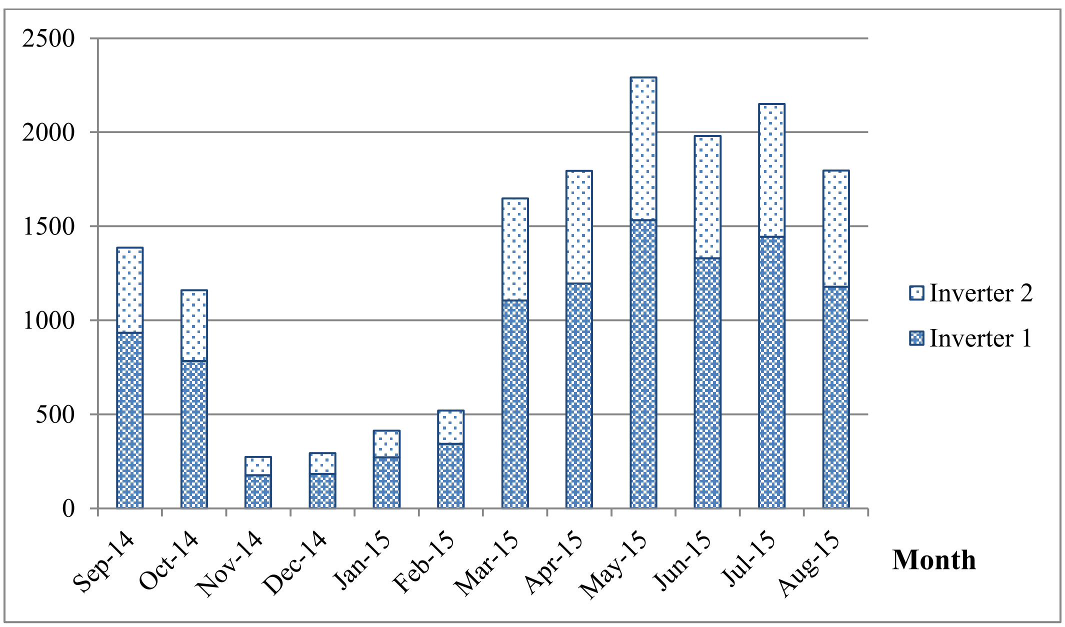

Fig. 5-19. Monitored Energy Generation

With the data from the SolarLog system, the monthly energy generation and solar radiation are displayed in Table 5-8. The correlation between the monitored energy generation and the average tilted solar radiation is quantitatively illustrated in Fig. 5-20, and the correlation can also be described using Eq. 5-14, with R^2 of 0.92.

Table 5-8 Monitored Energy Generation and Solar Radiation

Month	Energy Generation (kWh)	Horizontal Solar Radiation (kWh/m²/d)*
Sep-2014	1,386.47	3.77
Oct-2014	1,160.41	2.22
Nov-2014	273.22	1.27
Dec-2014	294.11	0.79
Jan-2015	413.16	1.27
Feb-2015	520.33	2.45
Mar-2015	1,649.37	3.79
Apr-2015	1,795.31	4.73
May-2015	2,291.94	5.27
Jun-2015	1,981.05	5.86
Jul-2015	2,150.6	6.35
Aug-2015	1,795.9	4.72
Total	15,711.87	

*: http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/timeseries.cgi

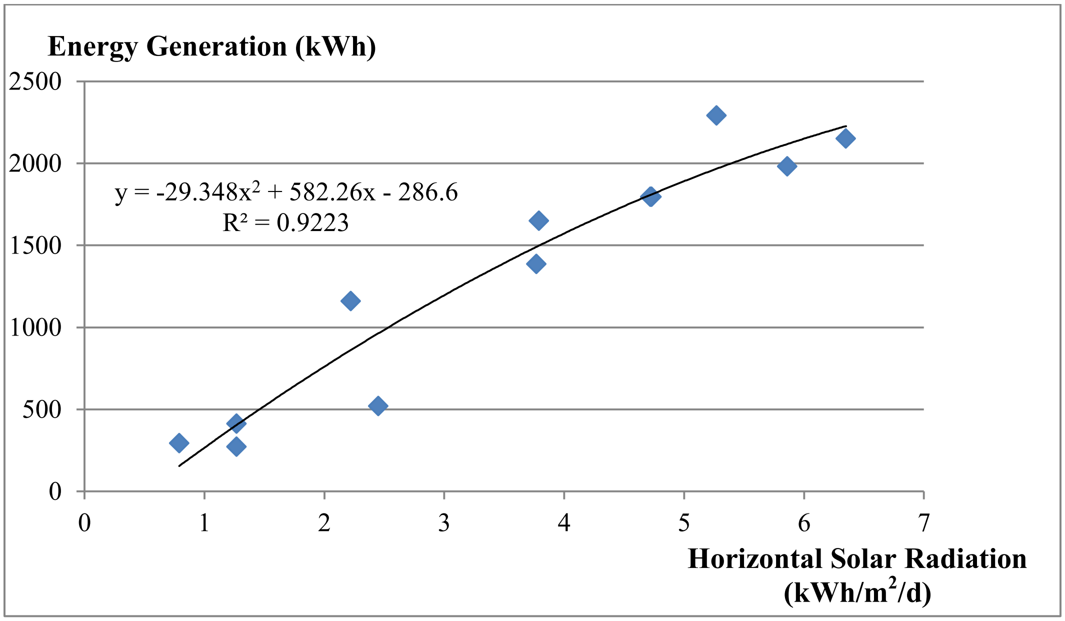

Fig. 5-20. Correlation Between Energy Generation and Tiled Solar Radiation

$$y = -29.348x^2 + 582.26x - 286.6 \quad (5\text{-}14)$$

where y is energy generation, and x is horizontal solar radiation.

5.5.2 Energy Balance Analysis

The energy balance is related to both energy generation and energy consumption, and varies from time to time. Considering HDDs & CDDs are the main factor for energy consumption, and solar radiation is a determining factor of energy generation, the correlation of energy balance, HDDs & CDDs, and solar radiation is analyzed in this section. The monthly HDDs & CDDs, solar radiation, and the energy balance are shown in Table 5-9 and Fig. 5-21; the correlation of energy balance with HDDs & CDDs and solar radiation can be observed from Fig. 5-21; in general, more energy balance is achieved when the HDDs & CDDs decrease and the solar radiation increases.

Table 5-9 Monthly HDDs & CDDs, Solar Radiation, and Energy Balance

Month	HDDs & CDDs[1]	Horizontal Solar Radiation (kWh/m²/d)[2]	Energy Balance (kWh)
Sep-2014	178.7	3.77	418.42
Oct-2014	316.5	2.22	–86.64
Nov-2014	745.0	1.27	–1904.46
Dec-2014	765.4	0.79	–1701.63
Jan-2015	795.8	1.27	–1681.96
Feb-2015	754.1	2.45	–1394.40
Mar-2015	524.8	3.79	228.00
Apr-2015	326.1	4.73	666.66
May-2015	203.3	5.27	1,365.72
Jun-2015	87.1	5.86	1,233.12
Jul-2015	80.7	6.35	1,185.72
Aug-2015	86.4	4.72	1,002.06

[1]: http://edmonton.weatherstats.ca/
[2]: http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/timeseries.cgi

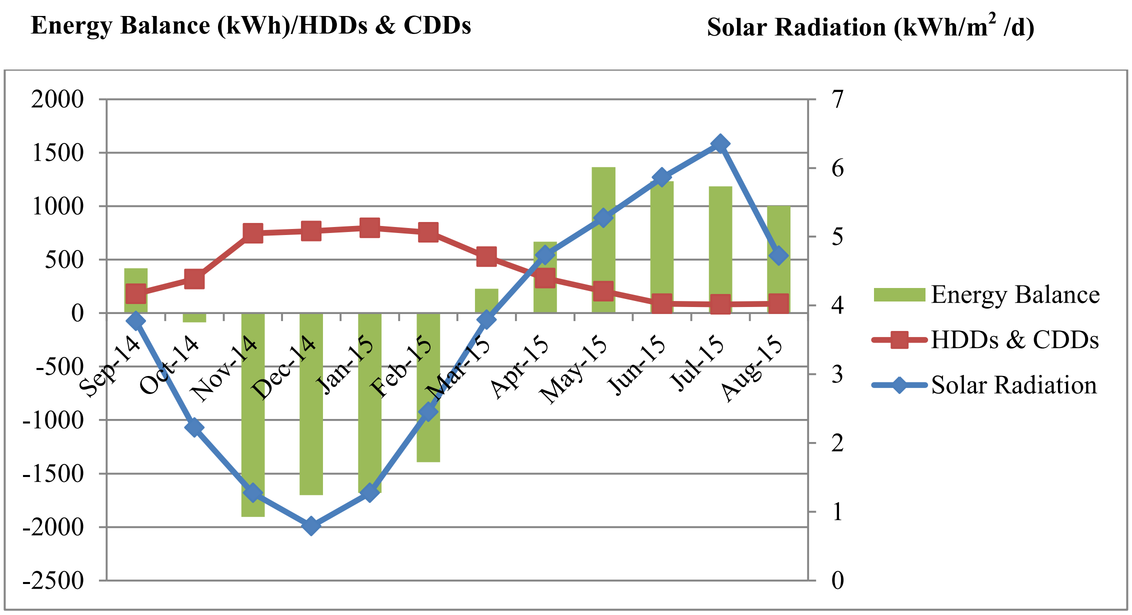

Fig. 5-21. Correlation of Energy Balance with HDDs & CDDs and Solar Radiation

From the daily view, the energy balance is correlated to sunrise and sunset. To have a statistical insight of energy balance, the hourly energy balance in September is averaged by day as an example, as shown in Fig. 5-22. It can be observed that, statistically, the energy surplus (positive balance) occurs between 8:00 a.m. and 5:30 p.m., while extra electricity is pulled from the grid during the night to mitigate the energy deficit (negative balance).

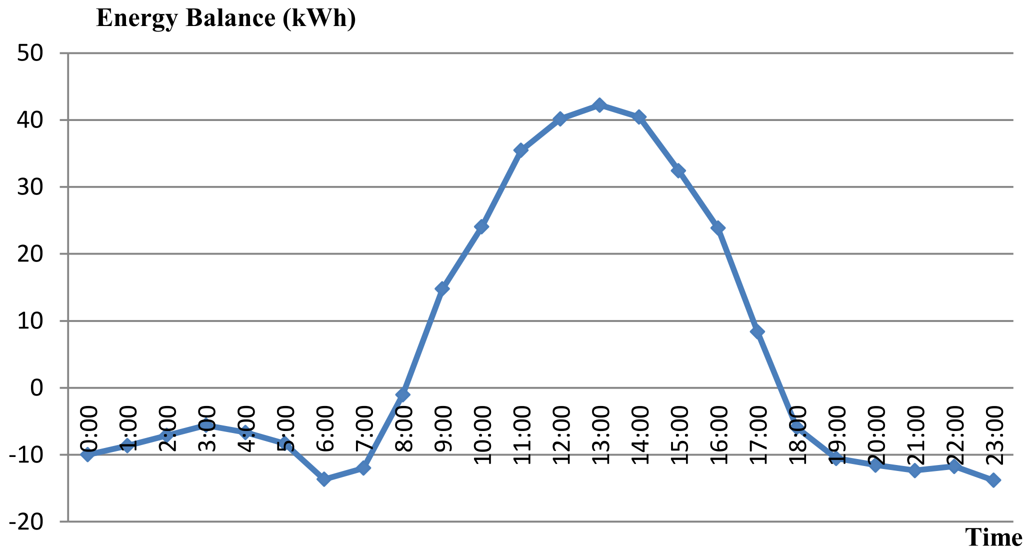

Fig. 5-22. Average Hourly Energy Balance for September

Another issue related to the energy balance is *the amount of energy generation consumed on-site instantly*, given the fact that there exists a price difference between pulling electricity from the grid and injecting electricity into the grid. To look at this issue in detail, the amount of energy generation consumed on-site instantly for two days is calculated as the example. As mentioned before, the energy measuring system records the electricity consumption and the balance at a time interval of 30 seconds, and Solar-Log records the electricity generation at 5-minute intervals. To combine the energy consumption and generation together, the time interval of consumption and balance is accumulated to 5-minute intervals. Two days with different weather conditions are taken as examples in this research, which are Sep. 15, 2014 and Sep. 24, 2014. An ideal weather condition occurred on Sep. 15, 2014, and the generation profile shows a perfect bell shape as shown in Fig. 5-23. The highlighted area in the chart represents the energy generation consumed instantly on-site, which accounts for 17% of the total energy generation. Sep. 24, 2014 was partly cloudy; thus, the solar generation was average, and the generation fluctuated. However, the energy consumption during that day was still mostly provided by solar PV as shown in Fig. 5-24, and the percentage of instant on-site use increased to 27%.

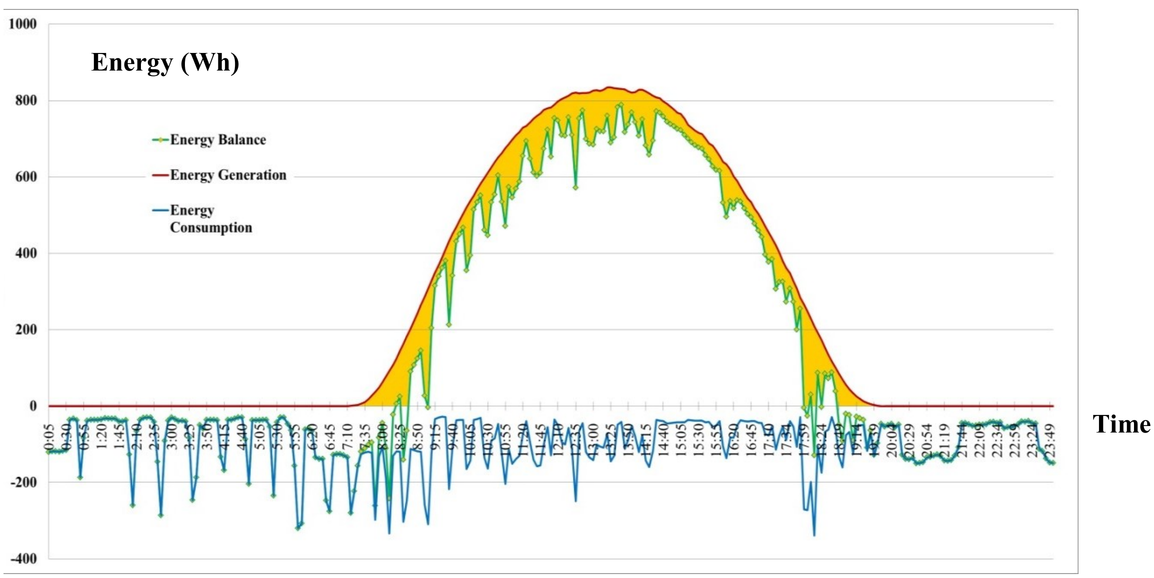

Fig. 5-23. Energy Balance on Sep. 15, 2014

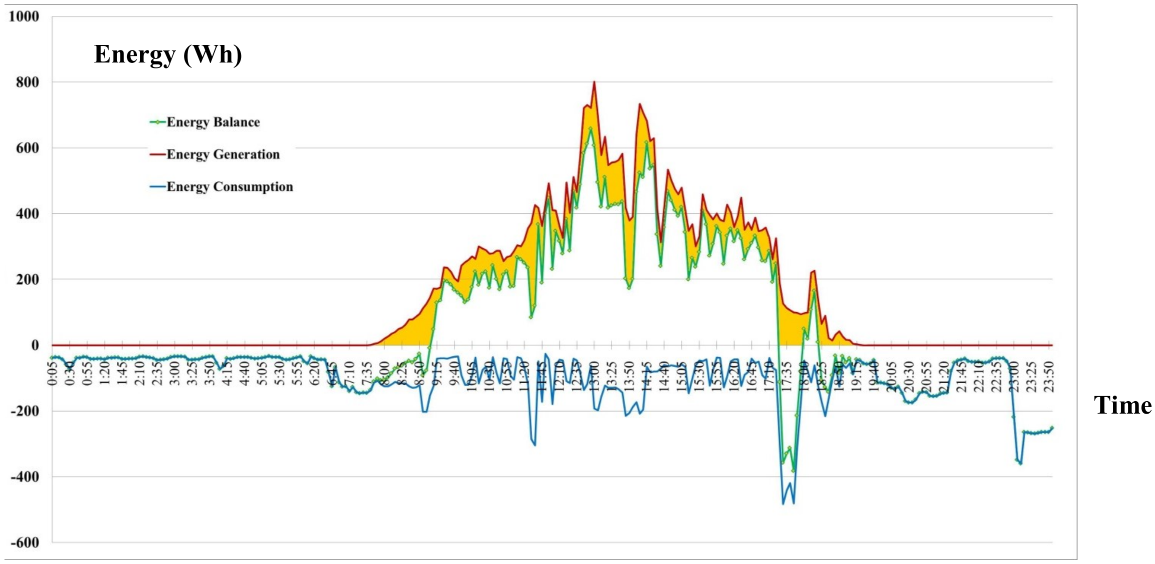

Fig. 5-24. Energy Balance on Sep. 24, 2014

The energy balance analysis provides the support information for assessing the size of electricity utility service and the main electrical panel; the analysis results also can be referred to in order to propose the extra electricity disposal solutions, i.e., storing on-site or injecting into the grid.

5.6 **Energy Control Strategies Based on Monitored Results**

Proper operation of NZEHs can reduce energy usage and help to achieve net-zero energy balance for NZEHs. Based on analysis of the collected data, the following suggestions are proposed for NZEH operation.

(1) Space heating is identified as the dominant energy consuming factor in such cold regions as Edmonton, accounting for more than 50% of the total energy usage. This issue appears severe for the winter; it is found that the highest energy usage for space heating occurs in November, 2014, which is more than *eight times* the lowest energy usage in August, 2015. Advancements in heat pump technology are expected to remedy this situation; however, it is known that the energy

efficiency of the air source heat pump drops when outdoor temperature is low according to the product manual. Based on analysis of the collected data, two recommendations are proposed in this research to mitigate this issue: (*i*) schedule the thermostat based on the occupant routine (e.g., set a lower indoor temperature in winter for the non-occupancy period of the day), by which to reduce the indoor and outdoor temperature difference and the energy usage for space heating and cooling; (*ii*) adjust the HRV operating mode according to the occupant routine and the number of occupants, by which to reduce the heat loss due to ventilation. For common HRVs, there are usually three operating modes, including 20 minutes operating per hour, 40 minutes operating per hour, and continuous operating, and a lower operating mode is recommended to be set for the non-occupancy period of the day.

(2) Phantom load is used to measure the stand-by load of plug-in devices and hot water tank during non-occupied days in this research. In the monitored NZEH, the lowest phantom load of 3.28 kWh/day is identified, which is equivalent to 1,198 kWh annually, and the stand-by load of hot water tank accounts for 34.34% of the phantom load. Two suggestions are proposed to address this issue in this research: (*i*) options of smart power strips are recommended for such plug-in devices as computer, monitor, stereo, TV, and coffee maker; (*ii*) a hot water tank blanket may be used to reduce the stand-by load of the hot water tank, which is demonstrated as Fig. 5-25.

Fig. 5-25. Hot Water Tank Blanket

(source: http://reflectiveenergy.ca/hot-water-tank-blanket/)

(3) Dryer is found to consume 3.5% of the annual energy usage, accounting for *more than five times* the energy used by washer. A daily average of 1.8 kWh of electricity is identified to be consumed by dryer in the monitored house. The occupants of NZEHs may consider drying clothes naturally on a drying rack in such dry regions as Edmonton.

(4) Most of the energy surplus occurs during day time; considering the electricity transmission loss and the price difference between pulling electricity from the grid and injecting electricity into the grid, pre-scheduling such appliances as washer, dryer, and range to operate during energy surplus periods is recommended in this research. The more electricity used on-site instantly, the more savings obtained.

Additionally, a monitoring system is recommended for NZEHs, which provides real-time indication and feedback to occupants, based on which occupants can adjust the operation of NZEHs. This suggestion is also acceptable by occupants, which is verified in the survey. The surveyed occupants are asked about the importance of energy consumption/generation monitoring; among the six NZEH occupants, four respondents indicate "must have"; one respondent "really wants" a monitoring system, and one cites "[would be] nice to have". Moreover, energy monitoring and the result report may be considered as an approach to strengthen the knowledge and information for NZEH occupants.

5.7 Summary

NZEHs are designed to achieve zero energy balance annually; however, the actual energy performance may differ from the expected. In this chapter, the actual energy performance of a NZEH in Canada is monitored and analyzed in detail. Across the monitored annual period between September, 2014, and August, 2015, the monitored NZEH is found to have an energy deficit of 669.38 kWh, which accounts for 4.1% of the total energy consumption. Among the energy consumers in the monitored NZEH, space heating and cooling is the dominant factor, representing 56.77% of the annual energy usage. DHW heating is the second-highest energy consumer, accounting for 12.9% of the annual energy usage. The dryer is found to represent 3.5% of annual energy usage, more than five times the energy used by the washer.

In this chapter, the total energy consumption of NZEHs is categorized into occupant-driven and less-occupant-driven. The former is entirely controlled by occupant activity by switching power on/off or plugging in/unplugging; the latter refers to continuous operation and energy consumption. Furthermore, the occupant-driven energy usage is analyzed for working days and non-working days. Among the occupant-driven energy consumption, phantom load is used to measure the stand-by load of hot water tank and plug-in devices during non-occupied days in this chapter. In the monitored NZEH, the minimum phantom load of 3.28 kWh/day is identified, which is equivalent to 1,198 kWh annually. Based on in-depth analysis, a polynomial model and two regression models (i.e., linear regression and regression decision tree) are proposed to describe energy consumption for the NZEH. The proposed models incorporate occupant behaviour, and can be applied for energy consumption prediction of NZEHs. Among the three proposed energy consumption prediction models, the linear regression model is proven to be the strongest in terms of R^2.

The energy generation and the energy balance are also analyzed in this chapter. It is found that the energy generation is formulated with solar radiation, and the energy balance is correlated with HDDs & CDDs, and with solar radiation. By combining energy consumption and generation data, an example of average hourly energy balance is demonstrated for September, 2014; the daily energy balance is analyzed with two days of different weather conditions considered as the example.

The energy performance monitoring and analysis provide feedback for NZEH operation, where proper operation will reduce energy usage and help to efficiently achieve net-zero energy balance. Based on analysis of the collected data, operation suggestions are proposed to reduce energy usage and to help achieve net-zero energy balance for NZEHs.

Chapter 6 Design Improvement of NZEHs

Based on energy simulation and energy monitoring, the aim of this chapter is to improve NZEH design through energy calibration and a two-step cost analysis. The research objectives include: (1) comparing the energy simulation with the monitored results; (2) calibrating the energy consumption/generation amount for future NZEH design, based on the energy comparison; and (3) identifying cost-effective design for NZEHs based on the energy performance calibration, and utilizing a two-step cost analysis.

6.1 Research Methodology

The research methodology of this chapter is illustrated in Fig. 6-1. The inputs of the methodology include: (1) estimated energy performance, (2) monitored energy performance, (3) energy performance acceptance, and (4) unit cost of building envelope and mechanical device options. Firstly, the actual energy consumption of the NZEH case is compared with the energy simulation model, and the comparison results are used for energy calibration. Secondly, by integrating the calibrated energy performance (energy consumption and generation) and the energy performance acceptance, which is achieved from the survey, qualified NZEH design scenarios are identified. Finally, cost analysis is conducted for the qualified design scenarios and the cost-effective design scenarios are identified. The occupant behaviour, the capacity of the solar energy system, and the energy simulation mechanism comprise the constraints of this research. The calibrated energy performance, the qualified NZEH design scenarios, and the cost-effective design scenarios are the outputs of this chapter.

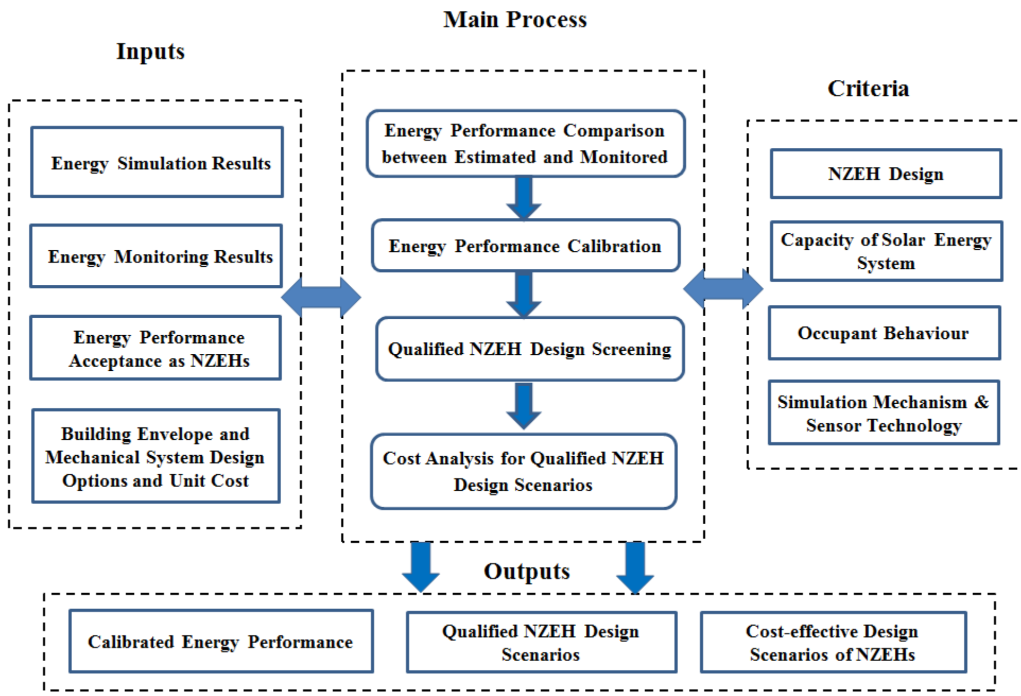

Fig. 6-1. Research Methodology

6.2 Energy Performance Comparison

As previously mentioned, HOT2000 and RetScreen are utilized as energy simulation tools during the design phase of NZEHs. The actual energy performance of the NZEH is compared with the results from the simulation models by category as follows.

6.2.1 Base Loads

The energy simulation model in HOT2000 is based on the assumption that two adults with two children live in a house, which has the same demographic composites as the actual occupancy, and the base loads reflect the electricity usage for such devices as appliances, exterior usage, lighting, and others. After aligning the energy consumption categories for base loads between HOT2000 modelling and the measured consumption, the comparison between the simulation results and the actual performance is conducted in Table 6-1. It can be observed that the base loads in the measured home are on average 50% lower than the simulation results and the actual consumption by appliances, lighting and others, and exterior uses all demonstrate lower usage than the energy simulation results for each month. The factor causing this difference is that the appliances and devices used as base loads are energy-star labelled (energy efficiency certification), which helps to reduce the amount of daily electricity consumption.

6.2.2 HRV

The estimated monthly energy consumption for HRV and the actual performance are displayed in Table 6-2, from which it can be observed that the estimated energy consumption mismatches the actual performance in most months, and the actual total energy usage of HRV is slightly higher than estimated. In HOT2000 modelling, the HRV operation is scheduled for each month according the seasons, and natural ventilation is applied for May through September, for which the operating time is scheduled as 0 (shown in Table 6-3). Comparatively, the HRV is operating using a different schedule set by the occupants, which contributes to the difference between the estimated and the monitored energy usage for HRV.

Table 6-1 Electrical Base Load Comparison

Item	Estimated (kWh/day)	Monitored (kWh/day)											
		14-Sep	14-Oct	14-Nov	14-Dec	15-Jan	15-Feb	15-Mar	15-Apr	15-May	15-Jun	15-Jul	15-Aug
Appliances	9	5.55	6.55	5.09	5.65	6.91	6.36	6.76	6.36	6.69	6.00	7.67	7.70
Interior lighting, exterior use, and others	15	7.17	5.73	4.72	4.90	4.96	4.62	8.89	4.51	4.73	4.50	5.13	4.77
Total	24	12.71	12.28	9.81	10.55	11.87	10.98	15.65	10.87	11.42	10.50	12.80	12.47
(Measured - Estimated) /Estimated		−47.0%	−48.8%	−59.1%	−56.1%	−50.5%	−54.3%	−34.8%	−54.7%	−52.4%	−56.2%	−46.7%	−48.1%
Average		−50.73%											

Table 6-2 HRV Energy Usage Comparison

Month	Estimated (kWh)	Measured (kWh)	Measured-Estimated (kWh)
Sep-2014	0.0	76.2	74.1
Oct-2014	90.6	66.5	−43.1
Nov-2014	84.7	70.0	−64.7
Dec-2014	85.8	32.8	−105.6
Jan-2015	85.1	27.7	−110.3
Feb-2015	77.7	22.2	−104.4
Mar-2015	87.9	30.5	−96.6
Apr-2015	87.6	54.3	−47.7
May-2015	0.0	55.1	53.9
Jun-2015	0.0	63.4	63.4
Jul-2015	0.0	70.7	70.7
Aug-2015	0.0	74.6	74.6
Total	**599.4**	**644.0**	−235.7
(Measured-Estimated) /Estimated		7.5%	

Table 6-3 HRV Operating Schedule

Month	Scheduled Operating Time (%)	Month	Scheduled Operating Time (%)
Jan	94.0	**Jul**	0.0
Feb	95.0	**Aug**	0.0
Mar	97.1	**Sep**	0.0
Apr	100.0	**Oct**	100.0
May	0.0	**Nov**	96.6
Jun	0.0	**Dec**	94.7

6.2.3 Space Heating and Cooling

The simulated and monitored energy consumption by space heating/cooling is displayed in Table 6-4, from which it can be observed: (1) the space heating/cooling consumes 32.1% more than estimated in total; (2) the measured energy consumption is lower than estimated in December and January, which may be caused by a warm winter; and (3) the measured energy consumption is higher than estimated in other months except December and January.

Table 6-4 Space Heating/Cooling Energy Usage Comparison

Month	Estimated (kWh) *	Measured (kWh)	Measured-Estimated (kWh)
Sep-2014	39	341.4	304.4
Oct-2014	243	616.6	392.3
Nov-2014	880	1,658.5	828.7
Dec-2014	1,890	1,462.7	−375.1
Jan-2015	2,175	1,496.4	−625.5
Feb-2015	1,278	1,420.6	192.0
Mar-2015	600	700.0	139.1
Apr-2015	186	575.3	403.6
May-2015	31	293.6	263.7
Jun-2015	0	221.2	221.2
Jul-2015	0	319.7	319.7
Aug-2015	0	194.4	194.4
Total	**7,322**	**9,300.4**	**2,258.5**
Measured-Estimated /Estimated		**27.0%**	

* Only energy usage for space heating is modelled in HOT2000

To investigate the causes of the difference between the estimated energy consumption for space heating and the monitored results, such weather parameters as maximum temperature, mean temperature, minimum temperature, and HDDs & CDDs are utilized as metrics for analysis in this research. The comparison of HDDs, CDDs, and temperature between the monitored period and the average of the last 25 years is presented in Table 6-5 and Fig. 6-2; from the comparison, it can be observed that: (1) there were less HDDs and more CDDs in the last year than the 25-year average, and (2) all of the maximum, mean, and minimum temperatures of the last year are higher than the 25-year average. Along with other well-known information in this regard (NASA 2015), the presence of a global warming trend can be concluded; global warming increases the energy usage for space cooling, which is not modelled for the monitored home.

Table 6-5 Weather Comparison*

	HDDs	CDDs	Maximum Temperature (°C)	Mean Temperature (°C)	Minimum Temperature (°C)
Sep., 2014 – Aug., 2015	4,711.5	152.4	34.1	5.4	−30.4
25-year Average	5,048.1	84.9	32.2	4.3	−32.1

* Source Data: http://edmonton.weatherstats.ca/metrics/hdd.html

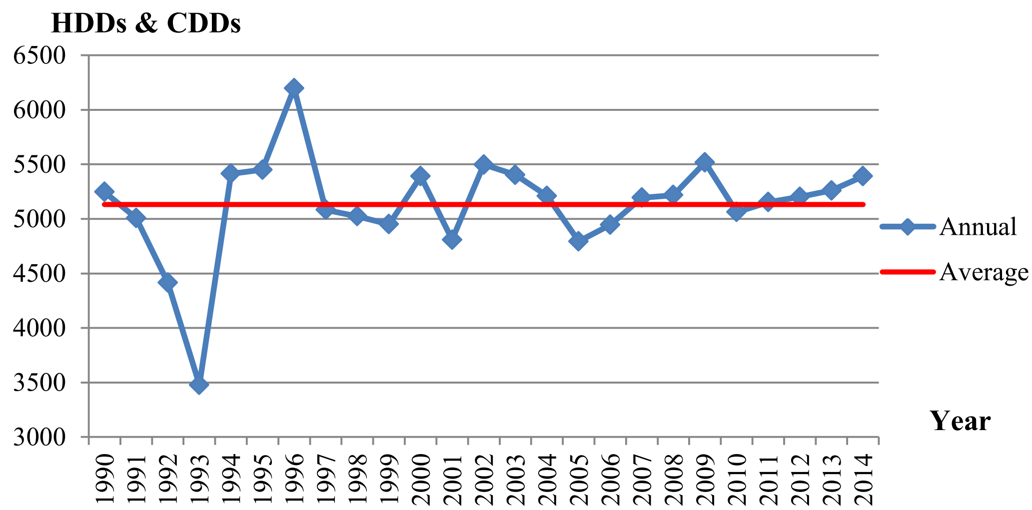

Fig. 6-2. 25-year HDDs &CDDs

As previously mentioned, the energy usage for space cooling is not modelled for R2000 mode in HOT2000, which brings in underestimated simulation results. Another reason causing the different is that the daily mean temperature is used to model the energy consumption of space heating in HOT2000, which results in zero energy usage modelled for space heating in June to August, as shown in Table 6-4; however, the reality is alternate heating in nights and cooling in days. The difference in the months other than June to August is mainly caused by the temperature variation.

6.2.4 Hot Water Heating

The simulated and monitored consumption by hot water tank is displayed in Table 6-6. The actual energy usage for hot water heating is lower than the simulated value, with approximately 14% less energy consumed by hot water tank during the monitored period. The energy usage for hot water heating is mainly determined by occupant behaviour, and the heat pump technology for the hot water tank applied in this monitored house helps to reduce the energy usage as well.

Table 6-6 DHW Energy Usage Comparison

Month	Estimated (kWh)	Measured (kWh)	Measured-Estimated (MJ)
Sep-2014	197.08	168.97	−28.1
Oct-2014	206.28	183.12	−23.2
Nov-2014	202.56	154.96	−47.6
Dec-2014	212.92	173.29	−39.6
Jan-2015	215.58	202.96	−12.6
Feb-2015	196.06	169.53	−26.5
Mar-2015	216.67	205.75	−10.9
Apr-2015	207.69	172.97	−34.7
May-2015	210.50	223.60	13.1
Jun-2015	197.61	148.31	−49.3
Jul-2015	201.72	177.68	−24.0
Aug-2015	200.81	138.43	−62.4
Total	**2,465.48**	**2,119.57**	**−345.9**
Measured-Estimated /Estimated		**−14.0%**	

6.2.5 Energy Generation Comparison

The monitored energy generation from SolarLog, the estimated energy generation from RetScreen, and the horizontal daily solar radiation from NASA database are listed in Table 6-7, from which it can be observed that 1,754 kWh less electricity was generated than the estimated, which accounts for 10.0% of the estimated. It also can be observed that the deficits occur from Nov., 2014 to Feb., 2015; however, the estimated and measured amounts of solar radiation during that period are very similar. Based on the above analysis and the weather data, it can be deduced that snow cover introduces side effects on solar PV performance in cold regions, which has also been proven in a study by Howell (2013).

Table 6-7 Energy Generation Comparison

Month	Estimated		Measured	
	Energy Generation (kWh)	**Horizontal Solar Radiation (kWh/m²/d)**	**Energy Generation (kWh)**	**Horizontal Solar Radiation (kWh/m²/d)**
Sep-2014	1,384	3.46	1,386	3.77
Oct-2014	1,204	2.18	1,160	2.22
Nov-2014	1,007	1.29	*273*	1.27
Dec-2014	762	0.77	*294*	0.79
Jan-2015	926	1.03	*413*	1.27
Feb-2015	1,262	2.05	*520*	2.45
Mar-2015	1,826	3.63	1,649	3.79
Apr-2015	1,785	4.80	1,795	4.73
May-2015	1,959	5.92	2,292	5.27
Jun-2015	1,794	5.96	1,981	5.86
Jul-2015	1,917	6.11	2,151	6.35
Aug-2015	1,640	4.75	1,796	4.72
Total	**17,466**	**3.50**	**15,712**	**3.54**
(Measured-Estimated) /Estimated			**−10%**	**1.10%**

6.2.5 Overall Comparison

The overall energy performance comparison is demonstrated in Table 6-8 and Fig. 6-3. It can be observed that: (1) the monitored NZEH consumes 15.7% less than estimated by HOT2000; (2) the solar PV system generates 10.0% less than estimated; and (3) except for the energy usage for space heating, the energy usage for HRV, DHW, and base loads are less than estimated by HOT 2000, with the details shown in previous sections.

Table 6-8 Overall Energy Performance Comparison

Comparison		Energy Consumption: HRV	Energy Consumption: DHW	Energy Consumption: Space Heating/ Cooling*	Energy Consumption: Base Loads	Energy Generation
Individual	Measured (kWh)	644	2,120	9,300	4,317	15,712
	Estimated (kWh)	599	2,465	7,322	8,760	17,466
	(Measured-Estimated) /Estimated	7.5%	−14.0%	27.0%	−50.7%	−10.0%
Overall	(Measured-Estimated) (kWh)	−2,765.0				−6,314.9
	(Measured-Estimated) /Estimated	−14.4%				−10.0%

* Only energy usage for space heating is modelled in HOT2000

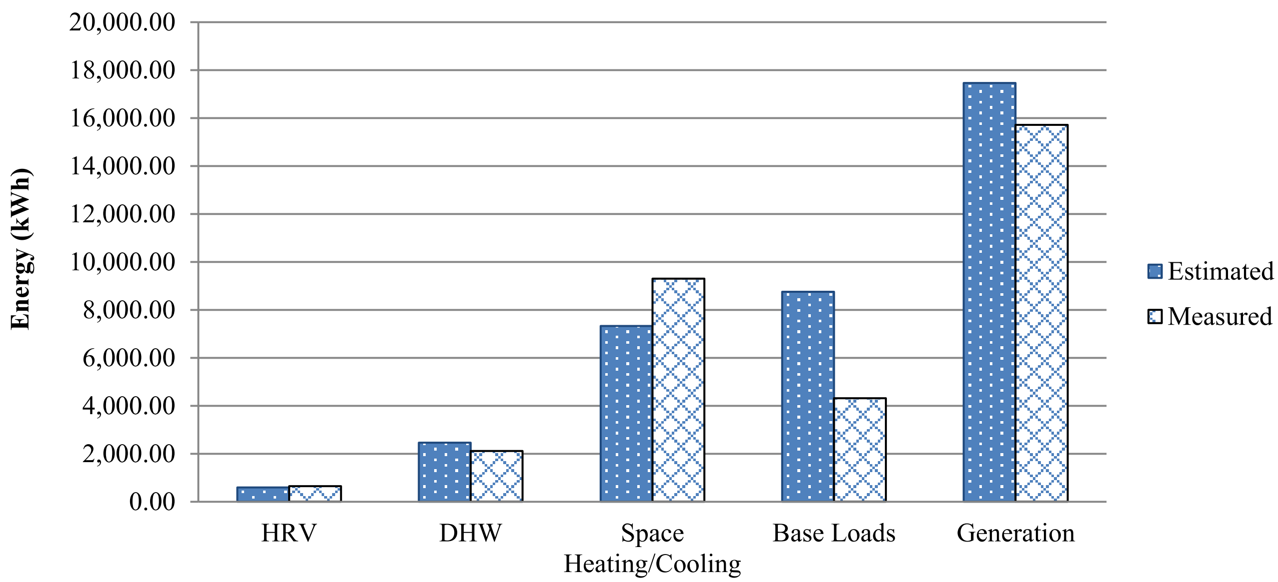

Fig. 6-3. Overall Annual Energy Consumption Comparison

6.3 Energy Calibration

Based on the analysis of the energy performance comparison by category, energy calibration is proposed for base loads, space heating and cooling, and energy generation, which entails non-trivial difference and obvious reasons causing the difference.

(1) Base loads: in order to have more evidence for base load calibration, the base loads from other monitored homes are analyzed in Table 6-9, from which it is can be observed: (a) all the measured base loads are less than the energy sizing in HOT2000, ranging from 9.4 kWh/day to 16.6 kWh/day; (b) less occupants in a home than the standard demographics (i.e., two adults with two children) results in less base loads. Based on both analyses from Table 6-1 and Table 6-9, a reduction of base loads is proposed for the energy sizing of the NZEH future design. The daily base load of 12 kWh/day is applied for the demonstration of the proposed two-step cost analysis below, and a specific reduction is proposed based on a large sample size in future research.

Table 6-9 Electrical Base Loads: Other Monitored Homes

House Type	Single Family Homes				Townhomes (kWh/day)	
	#118[a]	#221	#356	#360	#7804[b]	#7820[a]
Measured Base Loads (kWh/day)	16.5	16.2	12.7	16.6	9.4	11.9

[a] The detailed energy usage by HRV is not measured in the home, so the baseloads listed in the table included HRV energy usage;

[b] Only one person lives in the monitored home.

(2) Space heating and cooling: from the above comparison and analysis, it is found that the energy usage for space heating and cooling is underestimated, due to the following reasons: (a) the energy usage for space cooling is not modelled for R2000 mode in HOT2000; (b) daily mean temperature is used to model the energy consumption of space heating in HOT2000, which results in zero energy usage modelled for space heating in summer; (c) global warming is identified as a trend, which increase the energy requirement for space cooling. Therefore,

increasing the energy sizing for space heating and cooling is proposed for future design. An enlarging coefficient of 1.3 is proposed for the future development of this house model with the orientation in Edmonton.

(3) Energy Generation: considering the side effects brought by snow cover in the winter season, the calibration of energy generation using the collected data is proposed, and a 10% reduction is employed in this research, which can be validated in future research.

6.4 Two-step Cost Analysis

In the conducted survey, a question is designed to discover the obstacles deterring customers from buying an NZEH in the questionnaire to sales, and 7 out of the 10 sales respondents have chosen "too expensive" as the first obstacle of NZEH selling. The initial cost consists the bottleneck of NZEH promotion. To address this issue, a two-step method is proposed to minimize the initial cost for NZEHs in this section, by which the cost-effective design is identified for qualified NZEHs. The process of the proposed two-step method is described as follows. (1) Identify the qualified NZEH design: the first requirement that must be met for NZEH design is net-zero energy balance; the qualified NZEH design is screened based on the calibrated design simulation using data collected in the sensor-based monitoring and the energy performance acceptance as an NZEH, which is archived from the stakeholder survey. (2) Minimize the initial cost for qualified NZEH design: within the qualified NZEH design scenarios, cost analysis is conducted in order to improve the economic properties of the screened design scenarios, and the most cost-effective scenario is identified for NZEH design.

6.4.1 Qualified NZEH Design

The qualified NZEH design scenarios are screened from the total 16,200 simulated design scenarios, for which the energy calibration is applied using the collected data as mentioned above: (1) base loads are sized down by 50%; (2) energy usage for space heating is enlarged by 30%; (3) others remain as estimated by HOT2000; and (3) energy generation is reduced by 10%. Based on the energy calibration, a qualified NZEH design is determined by the combined energy performance (i.e., consumption & generation) and the energy balance acceptance as an NZEH by the stakeholders. The level of acceptance of energy performance from the survey results is referred to, and the acceptance level of 95% is applied in this section, where the acceptance is symmetrized for energy surplus. Thus, the design scenarios with energy generation greater than or equal to 95% of energy consumption and less than or equal to 105% of energy consumption are considered as qualified NZEH design scenarios. The qualified NZEH design screening is demonstrated in Fig. 6-4.

6.4.2 Cost-effective NZEH Design

Within the qualified NZEH design scenarios, the initial cost is analyzed for different building envelope and mechanical device options in order to identify the cost-effective design for NZEHs. The mathematical model of the two-step methodology is demonstrated in Eq. (6-1) through Eq. (6-8), in which the building envelope and mechanical device options are the variables, and the optimal scenario is selected by minimizing the initial cost. Meanwhile, such factors as geographical characteristics, orientation, and other design parameters are kept constant during energy simulation and cost optimization, as the constraints of the model.

$$Min[C(S_i)] \tag{6-1}$$

$$C(S_i) = C(S_0) + \Delta C_B^i + \Delta C_M^i \tag{6-2}$$

$$E(S) = HotSim(S) = HotSim(R^{BE}, R^{MS}) \tag{6-3}$$

$$R^{BE} = (MW, RF, EF, BW, BS) \tag{6-4}$$

$$R^{MS} = (DHW, SH, HRV) \tag{6-5}$$

$$S_i \in S^* \in S \quad i = 1,2, \dots m \tag{6-6}$$

s.t.

$$(1 - 5\%)EG \leq E(S^*) \leq (1 + 5\%)EG \tag{6-7}$$

$$(R, OR, ED) = (R_0, OR_0, ED_0) \tag{6-8}$$

where S_i is a qualified NZEH design scenario; m is the number of qualified NZEH design scenarios; $C(S_i)$ is the initial cost of scenario S_i; S_0 is the actual design of the NZEH; $C(S_0)$ is the initial cost of actual design, archived from purchase order; S is the overall proposed design scenarios; ΔC_B^i is the cost difference of building envelope for design scenario *i*, compared with the initial design; ΔC_M^i is the cost difference of mechanical system for design scenario *i*, compared with the initial design; $E(S)$ is the simulated energy consumption using Batch Version of HOT2000; R^{BE} and R^{MS} are the building envelope design options and mechanical system options, respectively; *MW* is the main wall design options, $MW = (x_1, x_2, \dots, x_L)$; *RF* is the roof design options, $RF = (y_1, y_2, \dots y_M)$; *EF* is the exposed floor design options, $EF = (z_1, z_2, \dots z_N)$; *BW* is the basement wall design options, $BW = (l_1, l_2, \dots l_O)$; *BS* is the basement slab design options, $BS = (m_1, m_2, \dots m_P)$; DHW is the domestic hot water tank options, $DHW = (a_1, a_2, \dots a_H)$; SH is the space heating furnace options, $SH = (b_1, b_2, \dots b_I)$; HRV is the heat recovery ventilator options, $HRV = (c_1, c_2, \dots c_J)$; S^* is the overall qualified NZEH design scenarios, meeting the energy acceptance levels; (*R, OR, ED*) are the geographical characteristics, orientation, and design parameters other than building envelope and mechanical components (these parameters are kept constant during the energy simulation); and (R_0, OR_0, ED_0) are the geographical characteristics, orientation, and design parameters other than building envelope and mechanical components of base scenarios.

The initial cost of the base scenario is archived from the purchase order. In order to calculate the cost difference for each qualified design scenario, the quantity is taken-off for each components of building envelope, and the unit cost is archived from RSMeans (building envelope) and online information (mechanical system) as follows.

(1) Building Envelope Quantities

Based on the HOT2000 modelling and the corresponding report, the quantities are archived for main wall, roof, exposed floor, basement wall, and basement floor, as shown in Table 6-10.

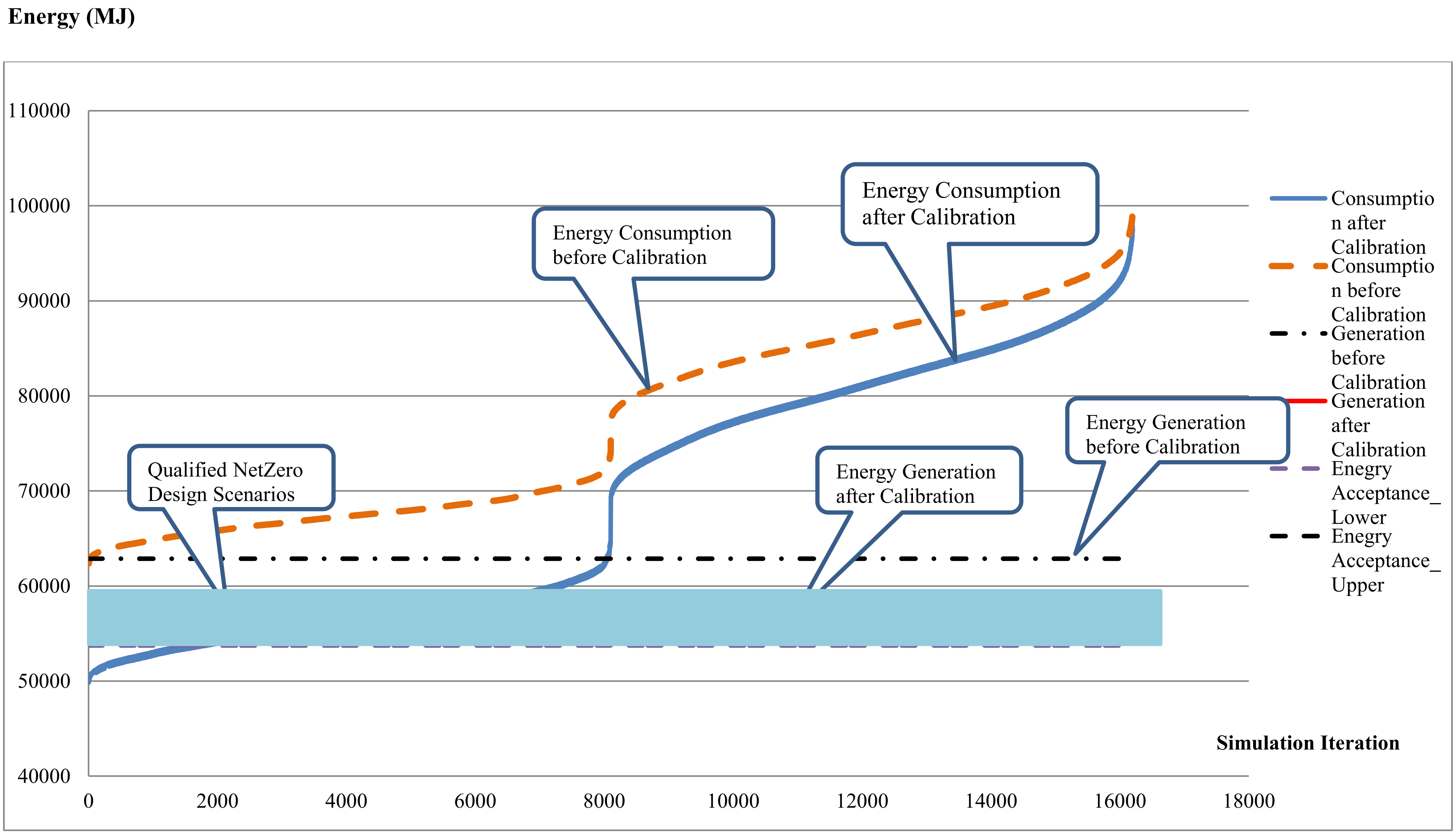

Fig. 6-4. Energy Calibration and Qualified NZEH Design

Table 6-10 Building Envelope Quantity

Building Envelope	Unit	Quantity
Main Wall	m^2	239.82
Roof	m^2	121.52
Exposed Floor	m^2	28.00
Basement Wall	m^2	104.71
Basement Floor	m^2	80.46

(2) Unit Cost of Design Options

The unit cost of the proposed building envelope design options is archived from RSMeans, which is an online unit cost database for construction industry; the archived unit cost of design options for main wall, roof, exposed floor, basement wall, and basement floor are listed in Table 6-11. Meanwhile, the unit cost of the proposed mechanical system options are referenced from online information, and the archived unit cost for space heating furnace, hot water tank, and HRV are listed in Table 6-12.

Table 6-11 Unit Price of Building Envelope Design Options

Main Wall		Roof		Basement Wall		Exposed Floor		Basement Slab	
Insulation	Unit Price ($/m²)	**Insulation**	Unit Price ($/m²)	**Insulation**	Unit Price ($/m²)	**Insulation**	Unit Price ($/m²)	**Insulation**	Unit Price ($/m²)
12.7 cm SPF + 6.73 cm Spider	70.13	8.89 cm SPF + 41.8 cm blown in	59.09	8.89 cm Batt + 8.89 cm SPF with drywall	38.16	17.78 cm SPF	66.20	10.16 cm EPS II	20.88
13.97 cm SPF	51.88	34.8 cm Blown-In	19.91	5.08 cm EPS + 14 cm mineral fibre	23.14	22.86 cm SPF	15.74	5.08 cm EPS II	10.44
7.62 cm SPF + 5.08 cm XPS	38.86	41.8 cm Blown-In	26.05	10.16 cm XPS + 14 cm mineral fibre	48.01	25.4 cm Batt	85.03	10.16 cm XTPS IV	35.31
10.16 cm SPF + 8.89 cm Batt	44.78	48.7 cm Blown-In	29.49	14 cm mineral fibre	12.70				
13.97 cm SPF + 10.16 cm EPS	87.19	69.6 cm Blown-In	39.83						

Table 6-12 Unit Price of Mechanical System Options

DWH	Price ($)	HRV	Price ($)	Furnace	Price ($)
Air source heat pump hot water tank (AO Smith Voltex, 80 Gal)	3,045.00	EKO1.5 (Venmar)	1,000.00	Air Heat Pump (Zuba Central)	7,118.00
Condensing Tank (Vortex AO Smith, Gas)	2,400.00	HE1.8 (Venmar)	1,812.00	Furnace (Trane XR95)	3,763.00
Tankless Water Heater (Instaneous, Navien NPE-240A, Gas)	2,180.00	Ultimate Air 200 DX	2,299.00		
Condensing Tank (Polaris, Gas)	3,389.00				

The initial cost is analyzed for the 5,322 qualified design scenarios based on the proposed methodology, and the cost-effective design is identified as $383,255 with R50 blown-in roof, 2×6 3″ SPF plus 2″ XPS filled main wall, R35 Batts insulated exposed floor, 2″ EPS II basement insulated slab, R22 mineral wool filled basement wall, heat pump space heating furnace, Ultimate Air 200 DXHRV, and tankless water heater. Compared with the initial cost of the actual design, which is $400,000, 4.2% of the initial cost can be saved. The proposed two-step cost analysis is capable of identifying cost-effective NZEH design, which also qualifies as NZEH.

6.5 Other Design Improvement Suggestions

(1) Passive design: as shown in Fig. 6-5, on the south-facing 12 m-long wall, only a 1.2 m × 1.0 m window is installed. To improve passive solar gain and passive lighting, more plentiful and larger south-facing windows are recommended for this house model.

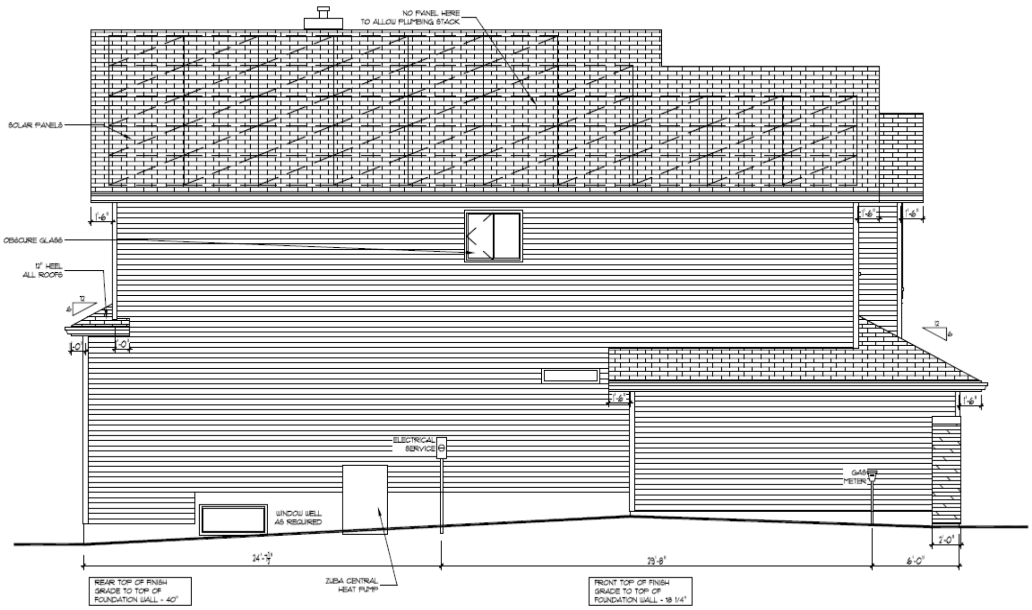

Fig. 6-5. Design Drawing: South-facing

(2) Cooling in summer: as discussed before, there were less HDDs and more CDDs in the last year than the 25-year average, and along with such evidences as sea level rise, glacial retreat, and natural disasters (NASA 2015), the presence of global warming as a trend can be concluded. However, as shown in Fig. 6-6, there are four large west-facing windows on the analyzed NZEH; with this regard, less and smaller west-facing windows are recommended for this house model, in order to reduce the energy requirement for cooling in summer.

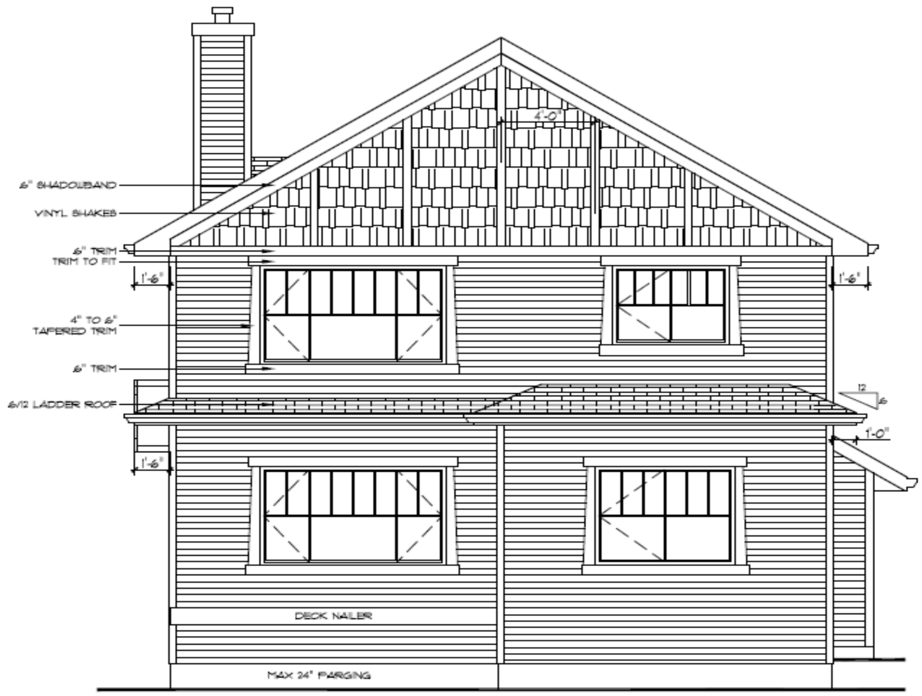

Fig. 6-6. Design Drawing: West-facing

(3) R-value of windows: although triple-glazed windows are used for NZEHs, the R-value of windows is still small, between R4 and R5. On the other hand, high R-value (R40 or so) walls are usually used for NZEHs. To reduce the R-value difference between windows and walls, two-layer triple/double glazed window systems are recommended for NZEHs, and more technical issues with this regard will be addressed in future research.

(4) HRV versus ERV: currently, HRVs are used in all of the studied NZEHs; however, ERV is recommended for such cold and dry regions as Edmonton, due to being more energy efficient (dPoint Technologies 2015). More field study will be conducted to compare the performance between HRV and ERV in future research.

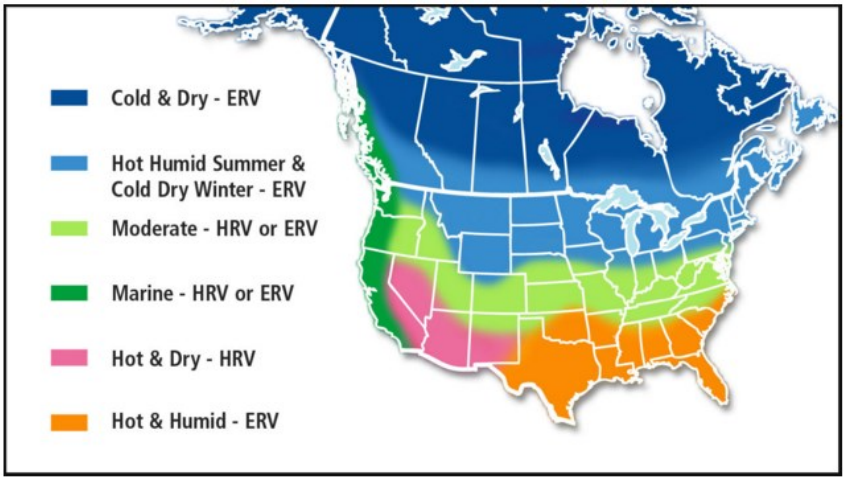

Fig. 6-7. HRV versus ERV

(Source: http://www.dpoint.ca/blog/item/181-erv-or-hrv-in-cold-climate-zones-time-to-end-the-debate)

6.6 Summary

The monitored energy performance of the NZEH is compared with the estimated performance in this chapter. The overall energy consumption is found to be 14.4% less than estimated from HOT2000: (1) HRV consumes 7.5% more than estimated; (2) DHW uses 14.0% less than simulated; (3) space heating and cooling consumes 27 % more than estimated; and (4) base loads are found to be 50.7% less than the energy sizing of the simulation. The solar PV system generates 10% less than simulated from RetScreen. The energy performance comparison is conducted in detail, and the causes of the differences are also identified. Based on the comparison and analysis, the following recommendations are proposed for future design of NZEHs: (1) less energy sizing is recommended for base loads, (2) larger energy sizing is suggested for space heating and cooling, and (3) sizing down the energy generation estimating of solar PV system is recommended for future design.

A two-step cost analysis method is proposed for NZEHs in this research, by which the most cost-effective design scenario is identified for NZEHs. First, based on the calibrated energy consumption and generation, as well as on the energy performance acceptance from the survey results, 5,322 qualified NZEH design scenarios are screened; then, an initial cost minimizing model is proposed, by which the cost-effective design is identified for NZEHs, and more design suggestions are recommended for future design based on the research results and analysis.

Thus, this chapter proposes a generic framework of energy calibration and cost analysis for the future design of NZEHs, which is based on energy simulation, energy monitoring, and a stakeholder survey.

Chapter 7 Conclusions and Contributions

7.1 Conclusions

This research proposes a generic framework to analyze stakeholders, design, and energy performance for NZEHs encompassing the following tasks. (1) Focus group and survey are applied for stakeholder analysis in order to investigate the market acceptance and the impacts of NZEHs on stakeholders. (2) Energy simulation is applied to simulate the energy performance of building envelope, mechanical system, and solar PV for NZEHs, and the simulation results are used for such analyses as energy modelling, factor ranking, and cost-effective design scenario analysis. (3) Sensor technology is utilized to monitor and assess the actual performance of NZEH cases, and the collected data is also used for energy modelling and calibration. (4) Incorporating the calibrated energy and the energy performance acceptance, the cost effective design scenarios are analyzed for NZEHs. This research results in holistic knowledge pertaining to stakeholders, design, and energy performance of NZEHs, which can be referred to in improving NZEH design and promoting NZEHs.

(1) Stakeholder Analysis

With the application of focus group study, 13 types of influential stakeholders are identified across the lifecycle of NZEHs: homebuyer, sales personnel, financial institution, developer, design and drafting personnel, estimator, project manager/coordinator, regulator, superintendent, inspector, trades/supplier, NZEH occupant, and warranty provider. Based on the identified stakeholders, the influence and interest are rated for each stakeholder by the focus group study attendees using a 1-10 scale, and it is found that stakeholders exert varying levels of influence and interest in different stages. The focus group study also helps to finalize the questionnaire design for each identified stakeholder, following which a survey is conducted. A survey link, created in Google Forms, is sent out via e-mail to contacts from industry and municipal directories, garnering 69 responses for this survey in total.

From the results of the survey, the energy performance acceptance as an NZEH in terms of energy generation versus consumption is found to be 96.12% on average, with design team and sales expressing higher acceptance level than homebuyer and occupants. Most of the homebuyers (10 out of the 13 homebuyer survey respondents) indicate an interest in buying an NZEH, and half of the potential home buyers indicate a willingness to accept the additional 5% price compared to conventional homes. It is also found that 9 out of 10 potential NZEH buyers would prefer to purchase a single-family home, rather than other home types. The demographic characteristics of potential homebuyers are also identified. NZEHs also introduce positive impacts on the occupants; all 6 NZEH occupant respondents agree that by having lived in an NZEH, their energy habits have changed and their overall energy awareness has improved. The NZEH occupant respondents also indicate that the most common positive aspect of living in an NZEH is the reduced utility bills for energy. Most of the NZEH occupant respondents (5 out of 6) believe that living in an NZEH has impacts on future generations in terms of energy savings and reduced environmental impact.

In the survey, a set of questions is also designed to identify the amount of effort in terms of priority, energy, and time among NZEH stakeholders and to compare it with that of conventional homes. All 69 respondents indicate equal or more effort expended on NZEHs compared with conventional homes, which reveals that the stakeholders of NZEHs are more dedicated than those of conventional homes, and that NZEHs introduce a positive impact on stakeholder relationships. Stakeholder relationships are also mapped as a social network utilizing UCINET as the tool.

The proposed stakeholder analysis results in holistic knowledge pertaining to the stakeholders of NZEHs, including the stakeholder influence and interest, the market acceptance, the impacts on the stakeholders, and the stakeholder social network. This research contributes to the body of knowledge on NZEH stakeholders.

(2) Energy Simulation

To analyze the energy performance of different design options of building envelope and mechanical system, including main wall, roof, exposed floor, basement wall, basement slab, space heating, hot water heating, and ventilation, the HOT2000 Batch Version is utilized for single-factor and multiple-factor simulation, in which 16,200 design scenarios are analyzed for the design of a NZEH. Based on the simulation results, curve-fitting and regression analysis are conducted for single-factor and multiple-factor simulation; the factor importance is also ranked for the building envelope and mechanical device variables. It is identified that space heating is a dominant factor among the eight simulated variables and clusters of energy profiles, and main wall is the most influential factor for building envelope. In order to examine the impact of temperature set-point, different temperature set-points are simulated with regard to energy usage for space heating, and the impact is analyzed. A linear function is found to fit well the relationship between energy usage for space heating and temperature set-point, and the temperature set-point is found to have a considerable impact on energy usage for space heating. RetScreen is utilized to simulate the energy generation for NZEHs. The designed NZEH case is estimated to consume 68,930.1 MJ annually, and the solar PV system is projected to yield 62,877.6 MJ in annual energy. The energy simulation provides quantitative information to support informed decision making for NZEH design, and builds a baseline for the energy calibration and cost analysis.

(3) Energy Monitoring

Sensors are utilized to monitor the actual performance of NZEHs, and the first monitored NZEH is found to have an energy deficit of 669.38 kWh (4.1% of the total energy consumption), across the monitored annual period between September, 2014, and August, 2015. Among the energy consumers in the monitored NZEH, space heating is the dominant factor, representing 56.77% of the annual energy usage. DHW heating is the second-highest energy consumer, accounting for 12.9% of the annual energy usage. The dryer is found to represent 3.5% of the annual energy usage, more than five times the energy used by the washer.

The total energy consumption is categorized into occupant-driven and less-occupant-driven. Furthermore, the occupant-driven energy usage is analyzed for working days and non-working days. In this research, among the occupant-driven energy consumers, phantom load is used to measure the stand-by load of plug-in devices during non-occupied days. In the monitored NZEH, the minimum phantom load of 3.28 kWh/day is identified, which is equivalent to 1,198 kWh annually. Based on in-depth analysis, a polynomial model and two regression models (i.e., linear regression and regression decision tree) are proposed to describe energy consumption for the NZEH. The proposed models incorporate occupant behaviour, and can be applied for energy consumption prediction of NZEHs. Among the three proposed energy consumption prediction models, the linear regression model is found to be the strongest in terms of R^2.

The energy balance is also analyzed, and the correlation between HDDs & CDDs and solar radiation is characterized. Based on the collected data and the energy performance analysis, energy control strategies are proposed to reduce energy usage and to achieve net-zero energy balance for NZEHs.

(4) Energy Calibration and Cost Analysis

The data collected is compared with the simulation results, and the overall energy consumption is found to be 14.4% less than estimated in HOT2000: (1) the HRV consumes 7.5% more than estimated; (2) the DHW uses 14.0% less than simulated; (3) space heating and cooling consumes 27% more than estimated; and (4) base loads are found to be 50.7% less than the energy sizing of simulation. The solar PV system generates 10% less than simulated from RetScreen. Based on the comparison and analysis, the following recommendations are proposed for future design of NZEHs: (1) less energy sizing is recommended for base loads, (2) a larger energy sizing is suggested for space heating and cooling, and (3) reducing the energy generation prediction of solar PV systems is recommended for future design.

Incorporating the calibrated energy and the energy performance acceptance from the stakeholder survey, 5,322 qualified NZEH designs are screened, based on which cost analysis is conducted in order to identify cost-effective design for NZEHs. The energy calibration and cost analysis will improve the future design of NZEHs in terms of accurate energy sizing and cost-effective design.

7.2 Research Contributions

(1) A stakeholder analysis framework is proposed for NZEHs by which holistic knowledge is obtained pertaining to the stakeholders of NZEHs, including stakeholder influence and interest, market acceptance, impacts on stakeholders, and stakeholder social network. This research thus contributes to the body of knowledge with regard to NZEH stakeholders.

(2) An automated simulation methodology is proposed for energy simulation, by which the energy performance of different design options of building envelope and mechanical devices is simulated automatically for NZEH design. Based on the simulation results, such information as the energy consumption model and the factor importance ranking is obtained. The energy simulation contributes a methodology for informed NZEH design decisions, and builds a baseline for the following energy calibration and cost analysis for NZEHs.

(3) An energy monitoring and analysis framework is proposed to assess the energy performance of NZEHs. Based on the data collected using sensor-based

monitoring, the energy performance is analyzed and modelled, and energy control strategies are proposed to reduce energy usage for NZEHs. Meanwhile, based on the comparison of the monitored and estimated energy performance, energy calibration is proposed for NZEH design.

(4) A two-step cost analysis method is proposed in order to identify cost-effective design scenarios for NZEHs. Based on the energy calibration, the qualified NZEH design scenarios are screened out incorporating the energy performance acceptance as an NZEH, and the most cost-effective design scenario is identified for an NZEH.

7.3 Research Limitations and Recommendations for Future Research

(1) Due to the fact that only limited NZEH cases have been developed regionally, the responses from each type of stakeholder are not sufficient, which constitutes a limitation of the present stakeholder study. More data need to be collected in future research, based on which thorough stakeholder strategies will be proposed to help promote NZEHs.

(2) More NZEH cases must be monitored and analyzed in future research. With a larger data sample, the results will be used to: (a) validate the research results with regard to the actual energy performance and energy calibration, and (b) identify the energy performance variations for different NZEHs.

(3) Such proposed NZEH design improvements as two-layer triple-/double-glazed window systems and replacing HRV with ERV need to be investigated in future research; more efforts can also be conducted with regard to the energy generation of solar PV systems in future research.

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Appendix 1: Publications (From 2011 Onwards)

Journal Articles:

Li, H. X., Gül, M., Yu, H., Awad, H., and Al-Hussein, M. (2016). "An energy performance monitoring, analysis and modelling framework for NetZero Energy Homes (NZEHs)." *Energy and Buildings*, 126, 353-364.

Li, H. X., Al-Hussein, M., Lei, Z., and Ajweh, Z. (2013). "Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation." *Canadian Journal of Civil Engineering*, 40(12), 1184-1195. **This paper was awarded Honourable Mention in the 2013 Stephen G. Revay Award.**

Li, H. X., Al-Hussein, M., and Lei, Z. (2011). "Incentive GA-based time-cost trade-off analysis across BOT project concession period." *Canadian Journal of Civil Engineering*, 38(2), 166-174.

Li, H. X., Gül, M., Don Mah, Yu, H., and Al-Hussein, M. "An integrated simulation and optimisation approach reducing CO_2 emissions from construction process." (Under review)

Li, H. X., Gül, M., Yu, H., and Al-Hussein, M. "Automated energy simulation and knowledge extraction for NetZero Energy Home (NZEH) design." (To be submitted)

Li, H. X., Patel, D., Al-Hussein, M, Yu, H. and Gül, M., "A stakeholder analysis framework for NetZero Energy Homes (NZEHs)." (To be submitted)

Conference Proceedings:

Li, H. X., Yu, H., Turnbull, D., Gül, M., Al-Hussein, M., and Mah, D. (2015). "Energy simulation of building envelope for NetZero Energy Home (NZEH) design." *Proceedings, International Conference on Construction and Real Estate Management (ICCREM)*, Luleå, Sweden, Aug. 11-12.

Li, H. X., Yu, H., Gül, M., Al-Hussein, M., and Chmiel, D. (2015). "An empirical study on the sustainability of panelized residential building construction." *Proceedings, International Construction Specialty Conference*, Vancouver, BC, Canada, Jun. 7-10.

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Liu, H., Lei, Z., **Li, H. X**., and Al-Hussein, M. (2014). "An automatic scheduling approach: Building information modeling-based on-site scheduling for panelized construction." *Proceedings, Construction Research Congress*, Atlanta, GA, USA, May 19-21.

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Li, H. X., Zhou, X., Morley, D., and Lucko, G. (2013). "Interruptability Analysis for Linear Scheduling with Singularity Functions." *Proceedings, 4th Construction Specialty Conference*, Montréal, QC, Canada, May 29-Jun. 1.

Appendix 2: Questionnaire Sample for Homebuyers

Introduction

1. **Background:**

Net-Zero Energy Homes (NZEHs) are defined as residential buildings which produce from renewable sources approximately as much energy as they consume on an annual base. NZEHs combine highly energy-efficient house design and onsite energy-producing technologies (e.g., solar panels / photovoltaics) to achieve a net-zero annual energy balance of consumption and production during occupancy.

2. **Objective:**

To identify the ***market acceptance conditions*** of NZEHs and the ***demographic characteristics*** of prospective homebuyers of NZEHs.

3. **Please Note:**

   1) No information that could possibly identify survey participants will be accessible to the industry partner.
   2) If you are interested in receiving a report on the results of this survey, please provide the email address: ______________________________

Questions for prospective home buyers

A. Information about yourself

1) What is your current employment status?
   a) Employed
   b) Self-employed
   c) Unemployed (Looking for work)
   d) Unemployed (Unable to work)
   e) Homemaker
   f) Student
   g) Retired

2) If applicable, what field are you working in?
   a) Agriculture, Forestry, Fishing and Hunting
   b) Mining, Quarrying, and Oil and Gas Extraction
   c) Utilities
   d) Construction
   e) Manufacturing
   f) Wholesale Trade
   g) Retail
   h) Transportation and Warehousing
   i) Information Technology (IT)
   j) Finance and Insurance
   k) Real Estate and Rental and Leasing
   l) Professional, Scientific, and Technical Services
   m) Education
   n) Health Care
   o) Social Work
   p) Arts, Entertainment, and Recreation
   q) Hospitality and Dining
   r) Public Administration
   s) Other Services
   t) Other, please specify:
   ____

3) Please indicate your approximate yearly household income before taxes. (Include total income of all adults living in your household.)
   a) Under $25,000
   b) $25,001 - $49,999
   c) $50,000 - $74,999
   d) $75,000 - $99,999
   e) $100,000 -$149,999
   f) $150,000 -$199,999
   g) $200,000 -$299,999
   h) $300,000 -$399,999

i) $400,000 -$499,999
j) $500,000 and over

4) What is your highest level of education?
a) No schooling completed
b) High School or Equivalent
c) Trade/technical/vocational training
d) Bachelor’s Degree or Equivalent
e) Master’s Degree or Equivalent
f) Doctoral Degree or Equivalent
g) Other (please specify): __________________

5) Please indicate your age group (years)?
a) 20 or under
b) 21 - 30
c) 31 - 40
d) 41 - 50
e) 51 - 60
f) 61 - 70
g) above 70

6) What is your buying profile?
a) Seeking investment
b) Seeking second home
c) Retiree
d) Downsizing family
e) Divorced / separated
f) Growing family with kids
g) Single / couple (no kids)
h) Other (please specify): __________________

7) Please indicate the number of children in your household under the age of 18.
a) None
b) One
c) Two
d) Three
e) Four or more

B. Market Acceptance

8) When buying a house, what is your primary concern?

a) Initial cost
b) Life-cycle cost (initial plus utility costs)

9) Were you aware of NZEHs prior to completing this survey?

c) yes
d) no

10) Are you interested in buying an NZEH?

a) yes
b) no

If yes, please answer question 11 to question 13:

11) What are the **reasons** contributing to your interest in buying an NZEH? (You can choose more than one answer.)

a) Reduced ***utility bills for energy***;
b) Better ***quality*** home;
c) More ***comfort***;
d) Permits a unique ***lifestyle;***
e) ***Reduced*** detrimental environmental impacts such as ***carbon emissions***
f) ***Positive impacts on future generations*** regarding energy saving and environmental protection
g) Other (Specify): ______________________________

12) What **type** of NZEH might you consider buying?

a) Single-family home
b) Duplex
c) Townhome
d) Apartment
e) Any of the above

13) **How much more** would you be willing to pay for an NZEH, compared with a conventional house?

a) No more
b) Up to 5% more
c) Up to 10% more
d) Up to 15% more
e) Up to 20% more
f) Other (Specify): _________________

If the answer for question 10 is no, please answer question 14:

14) What are the **reasons** deterring you from buying an NZEH? (You can choose more than one answer.)

a) Too expensive
b) Concerns in maintenance
c) No knowledge about NZEHs
d) Energy savings not a priority

e) Other (Specify): ________________

15) There are two house offers in the following table; one is a Net-Zero townhome in an excellent location, and the other one is a conventional single-family home in an average neighbourhood. The prices are comparable. Please choose your preference and specify the reasons.

Offer #	**Price**	**House Type**	**Floor Area (sq ft)**	**Location**
1	$480,000	Net-Zero Townhome	1,700	Excellent
2	$460,000	Single-Family	1,800	Average

a) Net-Zero townhome, reasons:

____

____

____

b) Single-family house, reasons:

____

____

____

c) Doesn't matter, reasons:

____

____

____

16) In your opinion, a home **<u>qualifies</u>** as a ***net zero energy home*** if the energy generation is

a) at least 100% of energy consumption
b) at least 99% of energy consumption
c) at least 95% of energy consumption
d) at least 90% of energy consumption
e) Other______________________________________

C. Thank You

1) Please forward/refer this survey to ***colleagues*** who may be interested in this survey.

2) Do you have any comments or feedback on this survey?

____

____

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Thank you for participating in this survey. Your responses are very important to us. Should you have any questions or concerns, please contact Lily: ho8@ualberta.ca